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IEEE Std 3007.2™-2010

Recommended Practice for the Maintenance of Industrial and Commercial Power Systems

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IEEE Recommended Practice for the Maintenance of Industrial and Commercial Power Systems

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Abstract: This recommended practice covers the maintenance of industrial and commercial power systems. It covers the fundamentals of electrical equipment maintenance, how to develop successful maintenance strategies, and the common testing methods used as part of an electrical equipment maintenance program.
Keywords: failure effect; failure mode; failure modes and effects analysis; failure modes, effects, and criticality analysis; hidden/latent failure; maintenance; predictive maintenance; preventive maintenance; probability; reliability; reliability-centered maintenance; safety-related work practices

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Introduction

This introduction is not part of IEEE Std 3007.2-2010, IEEE Recommended Practice for the Maintenance of Industrial and Commercial Power Systems.

IEEE P3000 Series

This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society as part of a project to repackage IEEE's popular series of "color books." The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material in the thirteen color books will be included in a series of new standards—the most significant of which will be a new book, IEEE Std 3000™, Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new book will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional "dot" standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a "dot" standard comes from a particular chapter of a particular color book. In other cases, material from several color books has been combined into a new "dot" standard. The material in this recommended practice largely comes from Chapter 5 and Chapter 6 of IEEE Std 902™-1998[a] and Chapter 8 of IEEE Std 446™-1995 [B29].[b]

IEEE Std 3007.2

The research and analysis of the optimum maintenance program for electrical equipment have been ongoing tasks of the maintenance manager for as long as electrical equipment has been used to support facility or plant operation. In spite of the findings from decades of analysis, maintenance programs still vary from breakdown maintenance programs to sophisticated preventive maintenance programs. Preventive maintenance programs may include predictive maintenance as well as a more sophisticated reliability-centered program. The many variables, from the types of electrical equipment to the types of applications in which they are used, make the universal definition of an exact maintenance program difficult. It is believed almost universally, however, that some form of maintenance is necessary.

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[a] Information on references can be found in Clause 2.

[b] The numbers in brackets correspond to the numbers of the bibliography in Annex A.

NFPA 70B-2006 [B45] states the following:

> "Electrical equipment deterioration is normal, but equipment failure is not inevitable. As soon as new equipment is installed, a process of normal deterioration begins. Unchecked, the deterioration process can cause malfunction or an electrical failure."

It is necessary to control equipment deterioration in order to maintain the use for which the equipment and systems were originally designed and installed. Although most parties would agree that preventive maintenance is necessary for the reliability of electrical power systems, there remains a wide disparity about the content of a preventive maintenance program.

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1. Scope

This recommended practice covers the maintenance of industrial and commercial power systems. It covers the fundamentals of electrical equipment maintenance, how to develop successful maintenance strategies, and the common testing methods used as part of an electrical equipment maintenance program.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE P3007.3™/D1, April 2010, Recommended Practice for Electrical Safety of Industrial and Commercial Power Systems.[1, 2, 3]

IEEE Std 902™-1998, IEEE Guide for Maintenance, Operations and Safety of Industrial and Commercial Power Systems (*The Yellow Book*).

[1] Numbers preceded by P are IEEE authorized standards projects that were not approved by the IEEE-SA Standards Board at the time this publication went to press. For information about obtaining drafts, contact the IEEE.
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3. Definitions, abbreviations, and acronyms

3.1 Definitions

For the purposes of this recommended practice, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.[4]

breakdown/corrective maintenance: Repair actions that are conducted after a failure in order to restore equipment or systems to an operational condition.

electrical equipment: A general term that is applied to materials, fittings, devices, fixtures, and apparatus that are a part of, or are used in connection with, an electrical installation. This term includes the electrical power generating system; substations; distribution systems including cable and wiring; utilization equipment; and associated control, protective, and monitoring devices.

failure effect: A description of how the failure affects the device involved in the failure as well as other equipment in the system.

failure mode: The way a piece of equipment fails, such as open or short circuited, or a description of what has failed to operate properly, such as loss of communication with a sensor.

failure modes and effects analysis (FMEA): The identification of significant failures, irrespective of cause, and their consequences. This term includes electrical and mechanical failures that could conceivably occur under specified conditions and their effect on system operation, adjoining circuitry, or mechanical interfaces.

failure modes, effects, and criticality analysis (FMECA): The identification of significant failures, their consequences, and their criticality. Analyzing failure criticality involves classifying or prioritizing the level of importance for each failure based on the failure rate and the severity of the effect of failure.

hidden/latent failures: An abnormal or detrimental condition about which no one would know in the normal course of operation. An example is a device failure that does not occur immediately at the time of overstress, but sufficiently weakens the device so that it later fails under normal operating conditions.

maintenance: The act of preserving or keeping in existence the conditions that are necessary in order for equipment to operate as it was originally intended.

predictive maintenance: The practice of conducting diagnostic tests and inspections during normal equipment operations in order to detect incipient weaknesses or impending failures.

preventive maintenance: The practice of conducting routine inspections, tests, and servicing so that impending troubles can be detected and then reduced or eliminated.

probability: A number expressing the likelihood of the occurrence of a given event, especially a fraction expressing how many times the event will happen in a given number of trials.

reliability: The probability that a product or service will operate properly for a specified period of time under design operating conditions without failure.

[4] *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at http://shop.ieee.org/.

reliability-centered maintenance (RCM): A systematic methodology that establishes initial preventive maintenance requirements or optimizes existing preventive maintenance requirements for equipment based upon the consequences of equipment failure. The failure consequences are determined by analyzing the possible failure modes of each component in an operating system and determining what effect that failure would have on the system and overall mission.

safety-related work practices: The procedures and actions defined in safety standards such as NFPA 70E-2009 [B46][5] to minimize the exposures and risks of working on or around electrical equipment.

3.2 Abbreviations and acronyms

ASD	adjustable speed drive
CT	current transformer
DF	dissipation factor
EMI	electromagnetic interference
EPM	electrical preventive maintenance
EPR	ethylene propylene rubber [cable]
FMEA	failure modes and effects analysis
FMECA	failure modes, effects, and criticality analysis
hi-pot	high-potential
ICCB	insulated-case circuit breaker
MCCB	molded-case circuit breaker
PD	partial discharge
PF	power factor
PILC	paper-insulated lead-covered [cable]
PT	potential transformer
RCM	reliability-centered maintenance
TTR	transformer turns ratio
UPS	uninterruptible power supply
VRLA	valve-regulated lead-acid [battery]
VT	voltage transformer
XLPE	cross-linked polyethylene [cable]

4. Preventive maintenance

The implementation of this recommended practice requires that the proper safety procedures be used as an integral part of the process. All of the recommendations provided here assume IEEE P3007.3[6] or the safety chapters of the prior document, IEEE Std 902-1998, are also being followed in conjunction with this document.

[5] The numbers in brackets correspond to the numbers of the bibliography in Annex A.
[6] Information on references can be found in Clause 2.

4.1 Program basis

Most people recognize the need for the maintenance of electrical equipment. The debate really focuses on how much maintenance is enough. The key to the discussion about the proper amount of maintenance centers on the economic balance between the cost of performing maintenance and the importance of reliable power. For example, a computer center with a downtime cost of US$100,000 or more an hour would justify a much more extensive maintenance program than would a small facility whose downtime cost is not as great.

Moreover, it has been shown that there is a balance to the amount of economic benefit that is achieved from performing maintenance. A lack of maintenance eventually results in failures and a high cost to a plant. Likewise, an excessive amount of maintenance may be wasteful and also may result in a high cost to a plant. It can also introduce additional opportunities for failure in several ways. The most obvious is that every time maintenance is performed is another opportunity for a mistake to be made by the individual(s) performing the maintenance. For some types of equipment, taking it apart itself introduces significant stress on the bolts, fasteners, etc. There are also cases in which only part of the system (usually a redundant part) is shut down while the rest of the system is in operation. Should a failure occur in the remaining system while the redundant part(s) are not available, the overall system experiences an outage. The optimum maintenance program lies somewhere in between. This balance point can vary for different types of facilities.

There are two benefits to having an effective electrical preventive maintenance (EPM) program. The first benefit is enhanced safety and system performance. The system operates as it was designed, and if a section of the distribution system does have a failure, the protection isolates the minimum amount of equipment. The second benefit is that both the costs of production loss and failure repair are reduced since the problems are located and corrected before a catastrophic failure occurs. Other intangible benefits include improved employee morale, better workmanship, increased productivity, reduced absenteeism, reduced interruption of production, and improved insurance considerations. In planning an EPM program, consideration should be given to the costs of safety, the costs associated with direct losses due to equipment damage, and the indirect costs associated with downtime or lost or inefficient production.

EPM is not only important for the reliability and integrity of electrical systems, it is also important for the safety and protection of people. With regard to personnel protection, Section 110.8(B)(1)(b) of NFPA 70E-2009 [B46] recommends that an arc-flash hazard analysis be performed and that an arc-flash protection boundary be established prior to commencing any work, and Section 130.3 of NFPA 70E-2009 provides the requirements for conducting such a study. All calculations for determining the incident energy of an arc and for establishing a flash protection boundary require the arc clearing time. This clearing time is derived from the engineering coordination study, which is based on what the protective devices are designed and adjusted to do. NFPA 70E-2009 also cautions that improper maintenance can adversely impact arc-flash hazards. An EPM program reduces hazards to employees as well as reducing the risk of failure or malfunction of electrical systems and equipment.

With the proper mixture of common sense, training, manufacturers' literature, and spare parts, proper maintenance can be performed to maximize the safety and reliability of power systems. Electrical equipment, if installed within its ratings and properly maintained, should operate trouble-free for many years. However, if operated outside of its ratings or without proper maintenance, catastrophic failure of the power system, circuit breaker, or switchgear can occur and cause not only the destruction of the equipment but also serious injury or even death of employees working in the area.

In order to protect electrical equipment and people, proper preventive maintenance should be performed on the equipment. In addition to the manufacturers' literature, several standards and guides assist users with electrical equipment maintenance. When the overcurrent protective devices are properly maintained and tested for proper calibration and operation, equipment damage and arc-flash hazards can be minimized.

Examples of existing standards and guides to help users understand electrical equipment maintenance are ANSI/NETA MTS-2007 [B3] and NFPA 70B-2006 [B45].

4.2 Design considerations

An optimum EPM program considers the overall design and operation of the facility. A key strategy for supporting preventive maintenance is to schedule maintenance activities during planned outages. For example, if the facility is required to deliver power only during periods of peak load, then arrange maintenance activities during off-peak hours. If maintenance outages require special planning and will have significant impact on plant productivity and operations, consider design features that will optimize the maintenance process and/or reduce the duration of the outage on critical plant loads. Typical design features include redundant switchgear, alternate power sources such as uninterruptible power supply (UPS) and diesel generator, or critical load protective devices like draw-out circuit breakers (rather than fixed-mount circuit breakers).

For the “24/7” (24 hours a day, 7 days a week) continuous power facilities, such as data centers, refineries, hospitals, and semiconductor manufacturing, the design of the facility is critical. For these types of facilities, the requirement is often that the electrical distribution system be “concurrently maintainable.” Concurrently maintainable means backup equipment and redundant power paths are available so maintenance can be performed on individual parts of the critical system without an outage to the critical loads. The maintenance is performed while the facility is in operation and the critical loads are in service.

Additional consideration should be given to the accessibility of the electrical equipment for maintenance. Electrical equipment location can be critical to the maintenance process. An example would be electrical equipment installed in a basement that has only stairway access through which testing equipment can be brought down to the electrical equipment. In addition, access to the back of switchboards or switchgear may be necessary in order to perform thorough maintenance and inspection, but may be difficult if such devices are mounted against the wall.

The environment in which the equipment is installed can play an important part in maintenance. Where equipment is mounted (indoors or outdoors) and whether it is properly enclosed and protected from dust, moisture, and chemical contamination are all factors that influence the frequency with which maintenance tasks should be performed.

The design phase is also the period in which the establishment of baseline data for the equipment should be considered. Baseline data can be established by including in the design specifications the acceptance or startup testing of the equipment when it is first installed. The manufacturer’s instructions for required testing prior to energization should always be followed. The InterNational Electrical Testing Association (NETA) provides detailed specifications for electrical power equipment in ANSI/NETA ATS-2009 [B1].

Design drawings are important to an effective maintenance program. As-built drawings such as single-line and logic diagrams should be current and controlled. An accurate single-line diagram is crucial for safety and effectiveness in the operation of the equipment. Such drawings help the operator to understand the consequences of operating a circuit that could result in an undesirable plant transient or unplanned mode of operation. In addition, equipment tags or identifiers in the field should be matched to drawing descriptions of equipment. This simple adherence to plant design standards and drawing control is significant to preempting the accidental energization and/or deenergization of equipment.

As part of the procurement of the electrical equipment, consideration should be given to the tools and instruments that are required to perform effective maintenance, such as hoists; manual-lift trucks that are used to remove and install circuit breakers; circuit breaker electrical operation test stations; and specialty maintenance devices such as spring blocking devices, manual charge handles, and contact erosion indicators. These tools and instruments will help to maximize safety and productivity. Finally, the installation, operation, and maintenance manuals should be obtained, maintained, and provided to the personnel performing the maintenance. Some facilities keep the instruction manuals in a spare cubicle of the switchgear itself.

4.3 Creating an electrical preventive maintenance (EPM) program

To be successful, an EPM program must have the backing of management. There should be the belief that operating profit is increased through the judicious spending of maintenance dollars. Financial issues should be considered when evaluating the need for continuous electrical power. These factors will help to dictate the level of importance that a facility places on an EPM program. The cost of downtime or lost production, the increased hazards to employees, and ways to minimize these costs and hazards through effective maintenance should also be considered.

In setting up any EPM program, it is essential to be thoroughly familiar with electrical safety, including how to properly perform lockout and tagout of the equipment to be maintained. IEEE P3007.3 provides detailed information on electrical safety, including lockout and tagout.

A complete survey of the plant should be performed. This survey should include a listing of all electrical equipment and systems. The equipment should be listed in a prioritized fashion in order to distinguish the systems or pieces of equipment that are most critical to the operation. The survey should also include a review of the status of drawings, manuals, maintenance logs, safety and operating procedures, and training and other appropriate records. It should be recognized that the survey itself can be a formidable task. It is likely that power outages may be required in order to complete the survey. The gathering of documentation is important. This task includes not only the drawings of the facilities, but also all the documentation that is normally provided by the manufacturer of the equipment. The manufacturer’s manuals should include recommended maintenance procedures, wiring diagrams, bills of materials, assembly and operating instructions, and troubleshooting recommendations.

Next, the necessary procedures for maintaining each item on the list should be developed. The manufacturer’s instructions along with NFPA 70B-2006 [B45] and ANSI/NETA MTS-2007 [B3] are valuable resources that provide much of this information. Procedures should also be developed that integrate the equipment into systems. People who are capable of performing the procedures should be selected, trained, and qualified. At some level of technical performance, it may be desirable to contract parts of the maintenance program and to qualify outside firms, particularly for functions that require special test equipment to perform.

Finally, a process should be developed to administer the program. This process may be manual or software-based. There are many commercially available systems with varying levels of sophistication.

Consideration should also be given to some of the less technical parts of the process. Maintenance planning should include the logistics of getting equipment in and out of the area to be maintained, general safety procedures, emergency procedures, and any record keeping needed before the maintenance activity. Also, planning should include follow-up maintenance, special lighting needs, availability of emergency power, and equipment-specific safety precautions. In addition, emphasis should be given to keeping electrical equipment accessible and not blocked by stored materials.

4.4 Reliability-centered maintenance (RCM)

4.4.1 Overview of RCM

RCM is a systematic and comprehensive approach to the maintenance of systems and equipment in which reliability is critical. RCM was initially developed by the airline industry, but has since been adopted by several other industries. The process involves performing a failure modes, effects, and criticality analysis (FMECA) and then determining for each component what is the appropriate and effective preventive maintenance activity. All possible failure modes and appropriate preventive maintenance are evaluated for each component; thus a program is established that is proven to result in improved facility equipment and systems reliability. Other benefits include improved safety, decreased repair costs, shorter outages, reduced overhaul frequency, and improved management of spare parts.

The following outlines the important philosophical topics surrounding RCM:

a) RCM is organized and documented common sense.

b) The focus of RCM is to analyze and make changes to current EPM program activities in order to improve their applicability and cost-effectiveness.

c) RCM evaluations determine the maintenance requirements of equipment based upon the function of the system and the way in which the equipment supports the function. An RCM-based maintenance program provides a technical basis for preventive maintenance activity that is not strictly based upon regulatory requirements, vendor recommendations, or industry standards.

d) RCM focuses preventive maintenance resources on equipment that is critical to maintaining important system functions. RCM emphasizes proactive, predictive maintenance techniques over traditional, time-directed maintenance techniques.

Typical implementation of an RCM program involves taking an existing EPM program and modifying it to align with the “critical path” or “mission” of the facility. In a data center, such alignment would include everything necessary to keep the computers running, which includes the UPS as well as the air conditioning system. All the systems in the critical path would receive priority, while the remaining, nonessential support systems would receive much less attention.

4.4.2 RCM procedure

RCM is a different philosophical approach to maintenance. Instead of focusing on preserving the individual pieces of equipment, with RCM the approach is to preserve specific functions the equipment performs. The importance of the functions to the overall mission of the facility determines where the maintenance efforts will be focused. Therefore, in order to do RCM effectively, the operating context for the systems to be evaluated must be well defined and understood. In the design phase, the operating context is often called *the basis of design*, the document that defines the expected performance of the facility, system, or processes to be built.

For example, if RCM were to be performed for the electrical distribution system in a high-rise building, the operating context of the emergency switchboard that supplies life safety equipment is different from the switchboard that supplies power to tenant space on the fifth floor. The two switchboards could be identical, but because the life safety switchboard has a greater importance to the entire building, it may warrant more maintenance than the switchboard for a single area of the building. Therefore, the analysis of each part of the RCM has to be based on the operating context of the systems or processes being evaluated.

a) Select the system(s) to be studied. Define the boundaries: What systems are included in this project? What systems are outside the scope of this project?

b) Gather the data, such as one-line diagrams, three-line diagrams, process control diagrams, schematic diagrams, vendor manuals, equipment history files, system operation manuals, system design specifications and descriptions, current equipment lists, and preventive maintenance procedures.

c) List the function(s) of each system or major component and any incorrect operation(s) (failures) for each system or component.

d) Prioritize the failure effects in order of severity, and make a list of the failure effects from highest impact to least severe. Depending on the system, there may be both primary and secondary effects, including the following examples:

    1) Primary effects: Safety of personnel, equipment damage, outage and production loss

    2) Secondary effects: Impact on customers, impact on company's public relations

e) Perform a failure modes and effects analysis (FMEA) of each system or major component:

    1) Failure mode is a description of what constitutes a failure (how the system or major component can fail to perform a required function).

    2) Failure cause is a description of why the failure occurred (root cause analysis).

    3) Failure effect is a description of how the failure mode impacts the function of the component involved in the failure as well as other equipment in the system.

f) Determine the probability of each failure using empirical data and statistical analysis, when possible. Estimate the probability of any failures that cannot be determined.

g) Identify significant failure effects based on the combination of severity and probability of occurrence.

h) For each failure mode of each system or major component associated with a significant failure effect, determine what maintenance (if any) could detect a hidden failure or prevent a future failure.

i) Estimate the economic impact of performing the maintenance. Compare the cost of performing the maintenance in terms of both direct and indirect (loss of production) costs to the potential savings of preventing a failure.

j) Revise the current maintenance program as necessary.

4.4.3 Example FMEA

To provide a better understanding of the RCM process, a portion of an RCM is provided here in which a FMEA is done for a 480 V main switchboard. (See Figure 1 and Figure 2.) Since the operating context for which the switchboard is providing power is not defined, this example covers only the part of the analysis that is common to all main switchboards.

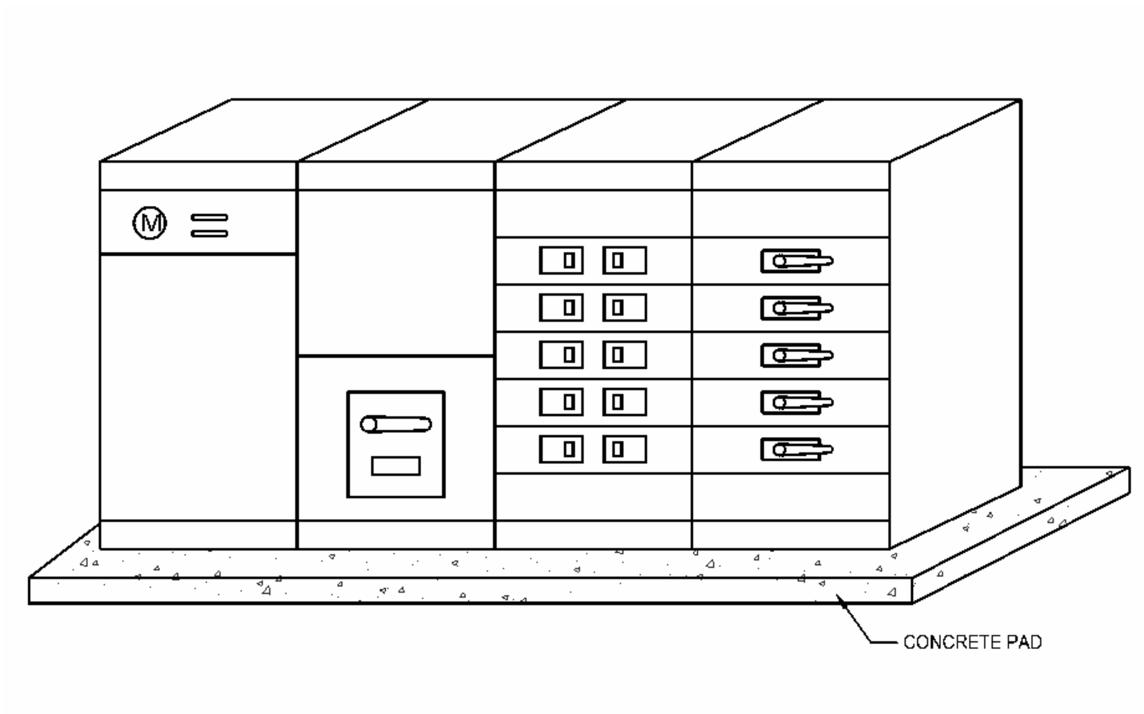

Figure 1—480 V main switchboard

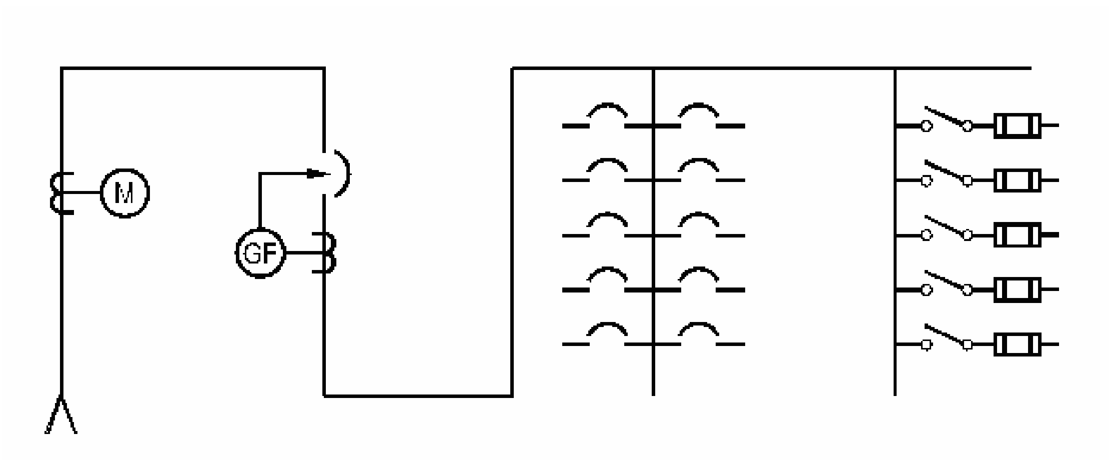

Figure 2—One-line drawing of 480 V main switchboard

For this example, the system consists of a 2000 A, 480 V main switchboard, without specifying the type of facility the switchboard serves. First, the aspects that are common to 480 V switchboards are discussed, and then how the type of facility the switchboard serves would influence what is optimum maintenance is discussed.

For the example system, the utility provides power with underground cables to a meter section in the switchboard. The switchboard has a 2000 A bolt-in, insulated-case, main circuit breaker. The circuit breaker has an electronic trip unit with long-time pickup and delay (for overload protection), instantaneous trip (for short-circuit protection), and ground-fault trip functions.

The switchboard has two distribution sections: one section with molded-case circuit breakers (MCCBs) that have thermal and magnetic trip elements and the other section with fused switches. The major components of the 480 V switchboard are as follows:

— Metal enclosure
— Circuit breakers
— Fused switches
— Control components and wiring
— Copper or aluminum bus bars, bolts, insulators, and barriers

The functions and failures of the 480 V main switchboard are as follows:

Function	Failure
Provide electrical power to the facility	Interruption of power to one or all of the loads
Provide a means to turn the power on and off	Failure to turn the power on or off
Provide a means to lock the power off (lockout and tagout)	No means provided; the circuit can be closed when locked out
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard or downstream of it	Failure to detect an abnormality; failure to isolate an abnormality; failure to isolate an abnormality safely
Provide a barrier between the energized parts of the switchboard and the enclosure to prevent shock hazard	Failure to prevent a shock hazard

To evaluate the effect of the failures, several levels of effects need to be examined. “Local effects” in turn create “secondary effects” until an “end effect” is reached. As an example, for the local effect of a “failure to isolate an electrical abnormality,” a short circuit causes high current to flow through one of the circuit breakers in the distribution panel, but it does not trip. There are a couple of possible secondary effects: The main circuit breaker can trip, or the fault can burn itself clear. The end effect to the facility can be loss of power, but no damage (other than the equipment that has the short circuit) if the main circuit breaker trips by the ground fault function. However, if the fault has to burn itself clear and starts a fire while it is burning, then the end effect may be the destruction of the entire facility. This situation is also likely to create an increased arc-flash hazard; therefore, the maintenance of the circuit breakers, to minimize the risk of failure, is crucial to the safety of personnel working on or near the equipment.

From the above example, it is obvious that some effects are much more significant than others. Addressing the local effects of a failure in the 480 V switchboard, it becomes apparent that the failures are, in order of severity, fire and arc-flash safety hazard, loss of power to the facility, and loss of power to a single circuit. “Loss of power” will be discussed later in the analysis. This analysis starts with the “fire and arc-flash safety hazard.”

WARNING

Electricity poses three threats to people: shock or electrocution from contact with live parts, burns from the arc-flash, and injury from the arc-blast of an electrical fault. The primary protection that the switchboard has to prevent injury to people is the metal covers around its outside. The covers have been designed to prevent contact with live parts. They also may provide some level of help in containing an arc-flash or arc-blast from a fault within the enclosure, particularly if the arc fault has low energy. However, only arc-resistant equipment has been designed to contain or safely divert the energy of an arc fault at the magnitude of the name plate rating. If the arc-flash or arc-blast from a fault is contained within the enclosure, it is also less likely to start a fire. In order for the covers to be effective, they must be securely latched, bolted, or screwed in place.

Therefore, it is obvious that the first and most significant hazard (shock or electrocution) can easily be avoided by keeping the covers on the switchboard and, when performing maintenance, **by turning the power off before the covers are removed**. See Table 1.

Table 1—FMEA for the switchboard of Figure 2

Functions	Failures	Component(s)	Local effect of failure	Cause of failure
Provide a barrier between the energized parts of the switchboard and the outside to prevent shock hazard and contain fault	Failure to prevent shock hazard	Metal covers	Fire or arc-flash safety hazard	Covers not installed
Provide a means to lock the power off (lockout and tagout)	No means provided	Mechanical device on the front of the breaker or fused switch	Safety hazard	No device provided
Provide a means to lock the power off (lockout and tagout)	Circuit can be closed when locked out	Mechanical device on the front of the breaker or fused switch	Safety hazard	Mechanical device on the front of the breaker or fused switch defective

The 480 V switchboard also provides overcurrent protection for electrical faults in the equipment it feeds by detecting overloads, short circuits, or ground faults and by automatically removing the electrical power. Since the example is a 2000 A, 480 V main switchboard, the main circuit breaker has ground-fault protection. The MCCBs and fuses have overload and short-circuit protection.

Following the above example for the fuses, Table 2 shows the functions, failures, component(s), local effect, and cause of the failure.

Table 2—FMEA for the switchboard continued

Functions	Failures	Component(s)	Local effect of failure	Cause of failure
Provide a means to turn the power on	Failure to turn the power on	Fused switch mechanism	Fused switch will not close	Operator or mechanism failure
Provide a means to turn the power off	Failure to turn the power off	Fused switch mechanism	Fused switch will not open	Operator or mechanism failure
Provide a means to turn the power on	Failure to turn the power on	Fuse	Fuse open	Defective fuse
Provide power to the load	Interruption of power to load, no abnormality exists downstream	Fuse	Fuse open	Defective fuse

The same diagram gets more complex for circuit breakers since there are more components and circuit breakers have more failure modes. See Table 3.

Table 3—FMEA for the switchboard further continued

Functions	Failures	Component(s)	Local effect of failure	Cause of failure
Provide a means to turn the power on	Failure to turn the power on	Circuit breaker	Loss of production	Operator or mechanism failure
Provide a means to turn the power off	Failure to turn the power off	Circuit breaker	Fire or safety hazard	Operator or mechanism failure
Provide a means to lock the power off (lockout and tagout)	No means provided	Mechanical device on the front of the breaker	Safety hazard	No device provided
Provide a means to lock the power off (lockout and tagout)	Circuit can be closed when locked out	Mechanical device on the front of the breaker	Safety hazard	Mechanical device on the front of the breaker or fused switch defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect abnormality	Circuit breaker trip unit, current sensing, wiring	Damaged or destroyed electrical equipment	Circuit breaker trip unit defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect abnormality	Circuit breaker trip unit, current sensing, wiring	Damaged or destroyed electrical equipment	Circuit breaker current sensing defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to detect abnormality	Circuit breaker trip unit, current sensing, wiring	Damaged or destroyed electrical equipment	Circuit breaker wiring defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to isolate it	Flux-shifter or shunt trip mechanism, wiring, circuit breaker mechanism	Damaged or destroyed electrical equipment	Flux shifter or shunt trip mechanism defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to isolate it	Flux-shifter or shunt trip mechanism, wiring, circuit breaker mechanism	Damaged or destroyed electrical equipment	Circuit breaker mechanism defective
Safely isolate electrical abnormalities (short circuits, overloads, or ground faults) in the switchboard	Failure to isolate it safely	Circuit breaker mechanism and arc chutes	Damaged or destroyed electrical equipment	Interrupting rating of circuit breaker is less than fault current available

Next consider the secondary effects, a phrase that refers to what happens to the system the switchboard is feeding as a result of a local effect. For example, a circuit breaker can fail to open and isolate a fault. What does that event cause to happen? The circuit breaker directly upstream could trip, and the secondary effect is that a larger part of the distribution system is without power. If the protection system was poorly designed, installed, or maintained, the secondary effect could include a fire in addition to the tripping of the circuit breaker upstream.

In the switchboard example, the next step would be to consider the equipment supplied by the switchboard. In an actual RCM, the load being supplied is a critical element in the process. The goal of the RCM is to optimize the maintenance of the power system so the facility can perform its intended mission. If the intended mission is to power a manufacturing facility 5 days a week for one or two shifts a day, the optimum maintenance would most likely be much different from the optimum for a manufacturing facility that operates 24/7.

The RCM process includes looking at each failure mode and all of the effects that each mode could cause. The local effect (for example, a circuit breaker fails to close) causes a secondary effect (for example, the pump fails to run), which ultimately causes the end effect (for example, a manufacturing line fails to start or it shuts down).

Once all of the effects have been determined, the effects are normally broken down into a gradient scale such as the one shown in Figure 3. Each failure is evaluated on two factors for the matrix: how detrimental is the effect to the mission of the facility and how probable is it that the failure will occur. In the matrix in Figure 3, the effects have been grouped into “catastrophic,” “critical,” “marginal,” and “minor.”

For most facilities, serious personnel injury or major equipment damage would be considered “catastrophic,” and significant loss of production would be considered “critical.” Reduced production may be considered “marginal,” and a failure that did not affect production may be considered “minor.”

The categories shown in the figure have been provided as an example. The gradient for an actual facility would have to be determined by the leadership for that facility. Depending on the facility, it could include such secondary effects as “failure to meet a delivery schedule” with an end effect of “loss of contract.”

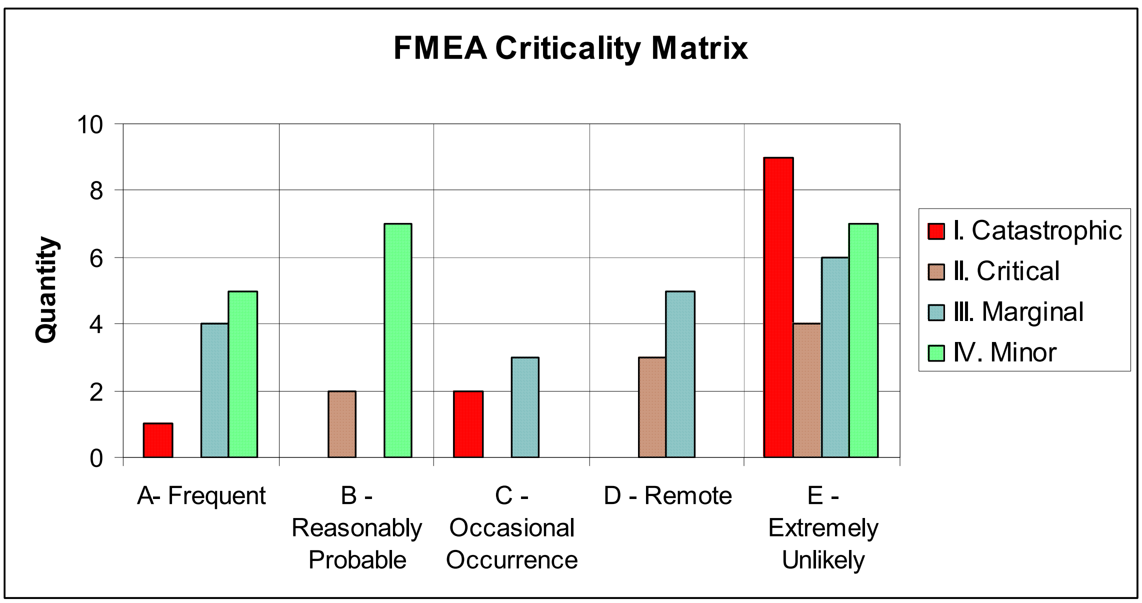

Figure 3—FMEA criticality matrix

The FMEA was performed to make the next step possible, which is the heart of the RCM analysis. The maintenance is now prioritized based on how detrimental the failure effect is and how likely it is to occur. If the effect is detrimental, but extremely unlikely, maintenance is not done. Maintenance is first perform where it will prevent failures that are both very likely *and* significantly detrimental. The process continues down the list of potential failures to the point of diminishing returns (failures that are least likely and have the smallest consequences).

4.4.4 Hidden/latent failures

As seen in the tables in the example above, some failures are "obvious" when they occur, such as the circuit breaker or fused switch that fails to close, with an end result of no power. These obvious failures are called *patent failures*. It should also be noted, however, that some failures are "hidden" failures. For example, the circuit breaker trip unit, which senses an overload or short-circuit condition, could be defective, and the only time the hidden failure is detected is when there is a fault on the circuit and the circuit breaker fails to operate. These hidden failures are called *latent failures*.

Therefore, the issue of latent failures should also be addressed as part of the RCM process. Some items, such as protective devices, require periodic testing to verify that they are operating properly. The trip unit and the current sensors for a circuit breaker are good examples of this type of device. The only way to find a defective trip unit is to test it. This situation is where the FMEA criticality matrix really becomes a valuable maintenance planning tool. "What does the circuit breaker supply power to?" becomes the driving force on how much maintenance it should receive. If the circuit breaker powers a lighting panel that is not critical to safety or production, it may not matter if it failed to trip, provided the upstream circuit breaker cleared the fault and its operation would also not be critical to facility operations. Therefore, no preventive maintenance or testing would be performed (such an approach is also referred to as a *run-to-failure*). However, if the circuit breaker provided power to the main production line, it would be important to maintain it.

Thorough acceptance testing of the equipment on initial installation can also be a significant factor in what is required to detect latent failures. If the facility had thorough acceptance testing performed, it is extremely likely that latent failures would have been found during the acceptance testing phase. A common example of this situation is reversed polarity on the neutral current sensor for the ground fault on the 480 V main circuit breaker. If the ground fault system were properly tested, this problem would be found and corrected before the facility was placed into service.

The probability of reversed polarity during installation is greater than the probability of the current sensor being defective or having the wrong ratio. Once the ground fault system has been tested, the polarity and the current sensor ratio have been verified; therefore, only the failure of a circuit breaker trip unit or current sensors while in service remains as potential latent failures.

The probability of a failure of the current sensors is less than that of the mechanism's failing to operate. Therefore, the mechanism should receive more attention than the current sensors. The probability of a failure of the trip unit is between the probability of a failure of the mechanism to operate (highest) and the current sensors (lowest). Therefore, the proper maintenance for the circuit breaker may be to perform cleaning and lubrication on the mechanism and secondary injection testing of the trip unit (using a special test set made by the manufacturer to test just the trip unit).

If acceptance testing was not performed, then the first time maintenance is performed, it would be advantageous to perform a primary injection test on the low-voltage circuit breakers and ground fault system (using a high-current test set that provides overload and short-circuit levels of current at low voltage) to make sure all the current sensors have the proper ratio and polarity. Primary injection testing provides a complete functional test of the circuit breaker at a low power level that does not damage the circuit breaker. An optimum maintenance program for circuit breakers in a manufacturing line is often to alternate between primary and secondary injection testing of the circuit breakers each time maintenance is performed (or primary injection every third time if the environment is clean and free of chemicals).

4.4.5 Specialized equipment

The maintenance of electrical power systems requires a wide range of materials, tools, and test equipment. Normal hand tools and maintenance supplies, such as cleaning materials, vacuums, and other shop-oriented tools, are necessary. At the other end of the spectrum are specialized test instruments, such as high-current

test sets that are necessary for primary injection of low-voltage circuit breakers. Some protective devices now require computers in order to perform calibration.

Safety equipment is also necessary for maintenance. This equipment may include safety grounds; arc-rated flame-resistant clothing, flash suits, and face shields; protective rubber insulating goods such as blankets, gloves with leather protectors, and sleeves; and insulated hand tools such as screwdrivers, wrenches, and pliers. Also needed for safety are portable voltage-rated meters or instruments to determine the presence or absence of voltage. This determination is necessary at each voltage level within the facility.

4.4.6 Record keeping

Each maintenance interval should be documented by listing the equipment that is being serviced and the maintenance procedures that are being applied. Data sheets that record the results of all tests should be completed and archived.

The test data should be analyzed by maintenance management in order to help determine the condition of the equipment and to determine the necessary repairs or activities. Repairs could be categorized by their critical nature, such as whether the repairs need to be done immediately before returning to service or whether they could be scheduled for a future date. The results of the maintenance records and the analysis of the data should lead management toward either increasing or decreasing the maintenance frequency or toward determining that the frequency and procedures are adequate.

Short-circuit, coordination, and arc-flash studies should be kept up-to-date. These documents not only help plant maintenance personnel evaluate the suitability of protective devices to interrupt in-plant fault currents with minimal safety risk and quantify potential arc-flash hazards, but also provide information that is necessary to set adjustable circuit breakers and protective relays for optimum selectivity and coordination. Proper coordination will minimize plant power outages in the event of equipment failure. A regularly scheduled EPM program is vital to the reliability of the protective devices.

4.5 Fundamentals of electrical equipment maintenance

4.5.1 Inspection and testing

The condition of electrical equipment is generally affected by the atmosphere and conditions under which the equipment is operated and maintained. Water, dust, temperature, humidity, corrosive fumes, vibration, and other environmental factors can adversely affect electrical equipment. Electrical equipment life can be extended dramatically by simple precautions that promote cleanliness, dryness, tightness, and the prevention of friction.

The thoroughness of maintenance procedures can be categorized into three different levels:

— Level 1—General inspection and routine maintenance
— Level 2—Inspection, general tests, and preventive maintenance
— Level 3—Inspection, specific tests, and predictive maintenance

Testing would typically include such tests as the following:

— Insulation tests
— Protective device tests

— Analytical tests (e.g., time-travel analysis, oil quality, dissolved gas-in-oil analysis, infrared surveys, and contact resistance measurements)
— Ground impedance tests
— System functional tests

Clause 5 describes each of these tests in detail.

The maintenance requirements of the following equipment should be evaluated as part of the maintenance program:

— Switchboards and switchgear assemblies
— Disconnect switches
— Circuit breakers
— Capacitors
— Surge arresters
— Current transformers (CTs)
— Potential (voltage) transformers (PTs)
— Protective relays
— Network protectors
— Fuses
— Batteries and battery chargers
— Meters and other instruments
— Alarms and alarm systems
— Grounding
— Ground detection schemes
— Transformers
— Insulating liquids
— Cables
— Busways
— Busducts
— Motor control center and motor starters
— Motor protective devices
— Motor drives
— Transformer auxiliary systems
— Rotating equipment (motors and generators)
— Lighting
— Wiring devices
— UPSs

— Transfer switches (automatic and manual)

— Test and safety equipment

4.5.2 Optimizing maintenance programs

In 4.4, RCM was discussed as the process of optimizing maintenance. It is a systematic and somewhat labor-intensive process that has proven to pay for itself in the long run. However, many facilities do not have the resources or the required management support to fully implement RCM. Such facilities can still benefit from understanding the RCM process.

Although the equipment and electrical distribution system designs for industrial and commercial facilities can be similar, the respective maintenance programs may be different. The maintenance on a draw-out 480 V circuit breaker in an industrial facility will probably be needed more often than on the same breaker in a commercial facility. However, the maintenance activities performed on the two circuit breakers will be essentially the same. Which circuit breakers are critical and need full maintenance versus which ones are not is determined by the RCM process. But it does not take a full FMEA and RCM to determine which circuit breakers feed the production line and which ones supply the office areas, etc.

Another significant part of optimizing maintenance and the RCM process is evaluating the maintenance procedures themselves. Many of the manufacturers' recommendations for maintenance include all the maintenance that can be performed on the equipment. Some of the maintenance procedures may be critical to the proper performance of the equipment, some may be important, and some may be of minimal value. An optimized maintenance program may cover all of the critical items and most of the important items, but completely ignore the items of minimal value. Here again the FMEA criticality matrix becomes valuable. It shows the detrimental failures that have a high probability of occurring; therefore, maintenance can be directed at those failures. A maintenance procedure that does not either help prevent the failure or locate a latent failure is not as valuable as one that does.

4.5.3 Equipment repair, replacement, or modification

Maintenance activities requiring equipment repair, replacement, or modification can be categorized by their importance to critical plant operations. Some activities must be accomplished before the equipment can be returned to service so the plant can be returned to operation. For example, support maintenance work may require material parts that are not stocked, and repairs or modifications cannot be accomplished until those items have been received and properly installed or integrated into the repair plan. Other repair work can be postponed; thus the electrical system can go back into service without undue risk. When conditions allow, noncritical repairs should be scheduled for a future date when other routine maintenance activities are in progress.

A part of EPM is determining which spare equipment or parts should be kept in stock, such as fuses, circuit breakers, and other components, in order to be able to repair critical items and return a shutdown facility to operation. This determination, like the maintenance procedure itself, requires an economic-benefit-versus-cost-of-inventory balancing act.

Spare parts management plays a vital role in EPM. Determining which parts should be available in stock or within hours' delivery is crucial to an operating plant's financial bottom line because receiving parts delays could prevent critical equipment from being returned to service and, in turn, a shutdown facility from returning to operation. Other considerations such as shelf-life of parts including electrolytic capacitors, batteries, printed circuit boards, and even some electromechanical relays are also paramount in spare parts inventory control.

4.5.4 Failure analysis

When equipment fails, it is important to understand the reason for the failure. Failure analysis, when done properly, locates the root cause of the failure, not just establishes what happened. This analysis is important in order to take the necessary steps to prevent similar failures in the future. Failure analysis involves an effort to reconstruct, at least mentally, the conditions that existed prior to failure and the events that led to the nature of the failure. Through this process the root cause can be determined.

Certain engineers specialize in forensic and failure analysis. These people, through their experience, are generally able to recognize failure patterns and to draw accurate conclusions much more readily than the untrained person. This specialty should be contracted when firms do not have that capability in house.

4.6 Inspection and test frequency

Equipment in a critical service would generally receive maintenance attention more frequently than other equipment. Manufacturers' service manuals should be consulted in determining an adequate frequency. They generally give frequencies that are based upon a standard, upon an average or typical interval, or upon operating conditions. This guidance is a good basis from which to start in determining the frequency for a given facility. Guidance for both maintenance frequency and routine inspections and tests can be found in NFPA 70B-2006 [B45] and ANSI/NETA MTS-2007 [B3]. Proper maintenance record keeping, together with periodic reviews, should reveal where adjustments to the frequency may be necessary, based on the actual effectiveness of the maintenance program.

5. Maintenance testing overview

5.1 Introduction

Maintenance testing is an important procedure that is used to detect deficiencies in electrical equipment before the equipment fails in service, often catastrophically. The very nature of electricity creates this need for testing. In normal operation, electrical equipment transports and utilizes energy. When a problem arises, such as an overload or a short circuit, the system should detect the problem and isolate it in a manner that minimizes safety risks. The only way to know whether the protective system works before it is needed is through testing. By simulating the various failure modes with nondestructive test methods, deficiencies in the system can be located and corrected. The testing helps to verify that, when the system is called upon to operate in a fault condition, it does its job properly and with minimal safety risks. Standards on how to minimize safety risks are available from a variety of sources, including IEEE, NFPA, and NETA.[7]

Electrical equipment is used in a variety of categories with respect to energy. Power flow starts with generation equipment. Next, electrical equipment such as transmission and distribution lines, power cables, and bus structures are used to transport energy. Other equipment, such as transformers, rectifiers, and converters, will change the form of the energy in some manner. A fourth category of equipment is used to detect and isolate problems. This category includes sensing devices, such as protective relays, along with interrupting devices, such as circuit breakers, switches, or fuses. The final category of equipment utilizes the energy to perform work in forms such as motors, solenoids, or electric heaters.

[7] IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://www.standards.ieee.org/). NFPA publications are published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269, USA (http://www.nfpa.org/). Copies are also available from the Sales Department, American National Standards Institute, 25 West 43nd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/). NETA publications are published by the InterNational Electrical Testing Association, 3050 Old Centre Ave., Suite 102, Portage, MI 49024, USA (http://www.netaworld.org)

Maintenance testing needs may vary with each of these categories. Keep in mind that the purpose of maintenance testing is to determine whether the equipment will continue to properly perform its function. In many cases, the testing consists of simulating different operating conditions and evaluating how the equipment responds.

5.2 Insulation tests

One characteristic that all types of electrical equipment have in common is the use of some form of insulation. At its most basic level, all electrical equipment has some part or parts that conduct electricity and other parts that do not. A bare overhead distribution line is held up by insulators and also utilizes the air around it for insulation. Transformer windings have insulation around each turn of the conductors and, in some cases, use oil, in addition, to raise the insulation value between the conductor and the grounded components.

The primary factor that determines the level of insulation that is required is the operating voltage. Other factors, such as current and frequency, also play a part; however, they are secondary to voltage. Therefore, the first consideration in testing insulation is whether it can support the required voltage without breakdown. This test is accomplished by measuring the leakage current that flows through the insulation medium when a voltage is applied.

There are almost as many types of insulation as there are different applications. However, they all have several things in common. Moisture and contamination decrease an insulator's ability to withstand voltage and increase the amount of leakage current that will flow. The insulation will also deteriorate with age. Overheating causes deterioration to be greatly accelerated. A common rule of thumb is that the life expectancy of the insulation is cut in half for every 10 °C increase in the long-term average operating temperature of the equipment.

Another characteristic that some types of insulation have is that, as the voltage rises, the insulation will maintain its integrity until it reaches the point of failure. Then, near the point of failure, the insulating capability drops rapidly, often accompanied by an arc or puncture in the insulation.

5.2.1 Electrical safety requirements for dc and ac testing

Before any electrical testing can be done, safety-related work practices must be established. Subclauses 5.2.1.1 through 5.2.1.6 provide specific safety-related work practices with regard to maintenance testing of electrical equipment. These safety-related work practices must be followed in order to minimize the risk to employees from the hazards associated with dc and ac testing.

5.2.1.1 Testing and test facilities

The subclauses of 5.2.1 relate to safety-related work practices for high-voltage and high-power testing performed in laboratories, shops, substations, and the field as well as on electrical lines and equipment. They apply only to testing involving interim measurements utilizing high voltage, high power, or combinations of both, and not to testing involving continuous measurements as in routine metering, relaying, and normal line work.

5.2.1.2 General requirements

The employer must establish and enforce safety-related work practices for the protection of each worker from the hazards of high-voltage or high-power testing at all test areas, temporary and permanent. Such work practices should include, as a minimum, test area guarding, grounding, and safe use of control and

measuring circuits. A means providing for periodic safety checks of field test areas should also be included. In addition, employees should be trained in safety-related work practices upon their initial assignment to the test area, with periodic reviews and updates as required.

5.2.1.3 Guarding of test areas

Safety-related work practices regarding test area guarding include the following:

a) Permanent test areas should be guarded by walls, fences, or barriers designed to keep employees out of the test areas.
b) In field testing, or at a temporary test site, where permanent fences and gates are not provided, one of the following means should be used to prevent unauthorized employees from entering:
    1) The test area should be guarded by distinctively colored safety tape that is strung and supported approximately waist high and to which safety signs are attached.
    2) The test area should be guarded by a barrier or barricade that limits access to the test area to a degree equivalent, physically and visually, to the walls, fences, or barriers designed to keep employees out.
    3) The test area should be guarded by one or more test observers stationed so that the entire area can be monitored.
c) The barriers should be removed when the protection they provide is no longer needed.
d) To prevent accidental employee contact with energized parts, guarding should be provided within test areas to control access to test equipment or apparatus under test that may become energized as part of the testing by either direct or inductive coupling.

5.2.1.4 Grounding practices

Safety-related work practices regarding grounding include the following:

a) The employer must establish and implement safety-related work practices for the grounding of equipment at the test facility.
    1) All conductive parts accessible to the test operator during the time the equipment is operating at high voltage should be maintained at ground potential except for portions of the equipment that are isolated from the test operator by guarding.
    2) Wherever ungrounded terminals of test equipment or apparatus under test may be present, they should be treated as energized until determined by tests to be deenergized.
b) Visible grounds should be applied, either automatically or manually with properly insulated tools, to the high-voltage circuits after they are deenergized and before work is performed on the circuit or item or apparatus under test. Common ground connections should be solidly connected to the test equipment and the apparatus under test.
c) In high-power testing, an isolated ground-return conductor system should be provided so that no unintentional passage of current, with its resultant voltage rise, can occur in the ground grid or in the earth. However, an isolated ground-return conductor need not be provided if the employer can demonstrate that *both* the following conditions are met:
    1) An isolated ground-return conductor cannot be provided due to the distance of the test site from the electric energy source.
    2) Employees are protected from any hazardous step and touch potentials that may develop during the test.

d) In tests in which the equipment grounding conductor located in the equipment power cord cannot be used to ground the test equipment due to increased risk of hazards to test personnel or the prevention of satisfactory measurements, a ground that the employer can demonstrate affords equivalent safety must be provided, and the safety ground must be clearly indicated in the test setup.

e) When the test area is entered after equipment is deenergized, a ground should be placed on the high-voltage terminal and any other exposed terminals.

    1) High-capacitance equipment or apparatus should be discharged through a resistor rated for the available energy.

    2) A direct ground should be applied to the exposed terminals when the stored energy has decayed to a level at which the safety risk is minimized.

f) If a test trailer or test vehicle is used in field testing, its chassis should be grounded. Protection against hazardous touch potentials with respect to the vehicle, instrument panels, and other conductive parts accessible to employees should be provided by bonding, insulation, or isolation.

g) The location of all temporarily installed equipment grounds should be documented so that they can be removed after the testing or maintenance is complete.

5.2.1.5 Control and measuring circuits

Safety-related work practices regarding control and measuring circuits include the following:

a) Control wiring, meter connections, test leads, and cables may not be run from a test area unless they are contained in a grounded metallic sheath and terminated in a grounded metallic enclosure or unless other precautions are taken that the employer can demonstrate as providing equivalent safety.

b) Meters and other instruments with accessible terminals or parts should be isolated from test personnel to protect against hazards arising from such terminals and parts becoming energized during testing. If this isolation is provided by locating test equipment in metal compartments with viewing windows, interlocks should be provided to interrupt the power supply if the compartment cover is opened.

c) The routing and connections of temporary wiring should be made secure against damage, accidental interruptions, and other hazards. To the maximum extent possible, signal, control, ground, and power cables should be kept separate.

d) If employees will be present in the test area during testing, a test observer should be present. The test observer should be capable of implementing the immediate deenergizing of test circuits for safety purposes.

5.2.1.6 Safety check

Safety-related work practices regarding safety checks include the following:

a) Safety practices governing employee work at temporary or field test areas should provide for a routine check of such test areas for safety at the beginning of each series of tests.

b) The test operator in charge should conduct these routine safety checks before each series of tests and should verify at least the following conditions:

    1) Barriers and guards are in workable condition and are properly placed to isolate hazardous areas.

    2) System test status signals, if used, are in operable condition.

3) Test power disconnects are clearly marked and readily available in an emergency.

4) Ground connections are clearly identifiable.

5) Personal protective equipment is provided and used as required by Subpart I of OSHA 29 CFR 1910 and by this subclause.

6) Signal, control, ground, and power cables are properly separated.

5.2.2 DC tests

The most common method of testing insulation integrity is to apply a dc voltage and measure the leakage current. The insulation resistance is then determined by dividing the voltage by the current. Many commercially available test instruments have specific voltage outputs and provide the readings directly in ohms. This testing is referred to as *insulation resistance testing*.

For low-voltage equipment, common test voltages are 100 V, 250 V, 500 V, and 1000 V. For medium-voltage equipment, test instruments are available with voltages of 2500 V, 5000 V, and 10 000 V. For most testing beyond 10 000 V, the test equipment no longer has a fixed output voltage. This testing is considered high-potential, or overpotential, testing, commonly called *hi-pot testing*, and the voltage is continuously adjustable so that it can be ramped up slowly. The leakage current is usually directly measured when hi-pot testing is being performed since the voltage is no longer fixed and getting a direct readout in ohms would be more difficult.

Basic electrical theory helps explain how dc insulation resistance testing works and what information it provides. A capacitor can be defined as a device for storing electrical charge that consists of two conductors separated by an insulator. From this definition, it can be seen that many electrical components, such as cables, bus bars, motor windings, and transformer windings, have capacitance to ground since the conductors of these items are separated from ground by an insulating medium. The amount of capacitance is determined by the sizes of the conductors, their proximity to each other, and the electrical properties of the insulation. When dc voltage is applied between the conductor and ground, the capacitor that is formed by the bus, cable, etc., and ground charges up. Once this charging is completed, the remaining dc current (called *leakage current*) that is flowing is due to the dc resistance of the insulation. By dividing the voltage by the leakage current, the value of the insulation resistance is obtained. It is common practice to measure the insulation resistance over a specific interval (to allow the capacitance to charge) and then record the final reading.

Since there is a fundamental difference between ac and dc voltage (ac is time-varying and dc is not), there is a corresponding difference in the voltage stress or gradient each applies to an insulation system. As noted in NFPA 70B-2006 [B45] and the IEEE 400 standards ([B25], [B26], [B27], and [B28]), there are significant differences between dc and ac dielectric tests and the stresses they apply to insulation systems. A primary shortcoming of dc testing is that the rise time of the dc voltage is relatively slow. The electric field gradient it produces in the insulation system is a function of the system capacitance, while it ultimately measures the resistive characteristics of the insulation system.

Power frequency ac testing on the other hand produces a stress gradient that is a function of the system impedance, which is what the insulation system will experience. The equipment will operate with a voltage that is changing from the maximum level high to the maximum level low (positive peak voltage to negative peak voltage) in half of one cycle or 8.33 ms at 60 Hz. The rapidly changing voltage causes a much higher dielectric stress on the insulation than a slowly rising dc voltage. This effect is easily demonstrated with an air gap. It takes a much higher dc voltage to bridge the insulation of an air gap than it takes to bridge the same air gap with an ac voltage.

Air gaps are used quite extensively in electrical systems from low-voltage panels to high-voltage power lines and often are a significant part of the insulation system. Most low-voltage panels and switchboards have bare bus and rely on the air gap between them for insulation. Therefore, the recommended practice is

to test the insulation integrity of ac equipment with ac voltage, as it is a much more effective test. Cable testing is the one exception to this guideline since air is not a primary factor in the insulation.

5.2.2.1 Insulation resistance tests

Insulation resistance tests (dc tests) are typically performed on motors, circuit breakers, transformers, low-voltage (unshielded) cables, switchboards, and panel boards to determine whether degradation due to aging, environment, or other factors has affected the integrity of the insulation. This test is normally conducted for 1 min, and the insulation resistance value is then recorded.

As mentioned earlier, the electrical properties of the insulation and the amount of surface area directly affect the capacitance between the conductor and ground and, therefore, affect the charging time. With larger motors, generators, and transformers, a common test is to measure the “dielectric absorption ratio” or the “polarization index” of the piece of equipment being tested. The dielectric absorption ratio is the 1 min insulation resistance reading divided by the 30 s insulation resistance reading. The polarization index is the 10 min (continuous) insulation resistance reading divided by the 1 min reading.

Both of these tests may provide additional information about the quality of the insulation. Some types of insulation, particularly some of the older types used in dry transformers and motor windings, become dry and brittle as they age and thereby become less effective capacitors. Thus, a low polarization index (less than 2.0) may indicate poor insulation. Even though insulation may have a high insulation resistance reading, there could still be a problem since the motor and transformer windings are subjected to strong mechanical stresses on starting.

The type of insulation is also a significant factor to consider when performing a polarization index. Many of the new plastics do not deteriorate like the paper-based insulations of the past. They also have extremely high resistance for the 1 min reading; therefore, the polarization index will be very low.

With the exception of electronic equipment (which can be damaged by testing), insulation resistance testing is normally done on most types of new equipment and is also part of a maintenance program. It is a good practice to perform insulation resistance testing on switchgear and panel boards after maintenance has been performed on them and just prior to reenergizing them. This scheduling prevents reenergizing the equipment with safety grounds still applied or with tools accidentally left inside.

As stated in 5.2.2, the recommended practice is to test the insulation integrity of ac equipment (other than cables) with ac voltage. Therefore, the dc insulation test is used to determine whether the equipment is ready for an ac overpotential test and for cable testing.

5.2.2.2 Hi-pot (overpotential) testing

Hi-pot testing, as its name implies, utilizes higher-than-rated voltage in performing the tests. It is utilized on low-voltage (0 to 1000 V), medium-voltage (1000 V to 100 000 V), and high-voltage (100 000 V to 230 000 V) equipment. (See Figure 4.) As stated earlier, the leakage current is usually measured. In some cases, such as in cable “hi-potting,” the value of leakage current is significant and can be used analytically.

In other applications, such as switchgear hi-potting, ac voltage is used, and the testing is a pass/fail type of test. “Passing” requires sustaining the voltage level for the appropriate time (usually 1 min). The capacitance varies significantly based on the size and physical layout of the switchboard, switchgear, or panel. Therefore, if the equipment under test holds the overpotential for the required time, it passes, regardless of what the value of leakage current may be.

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Figure 4—Circuit breaker hi-pot testing

5.2.2.3 Low-, medium-, and high-voltage cable testing

Most cables that are rated for use at voltage levels up to 600 V are unshielded. Since there is no shield on the individual conductors in most low-voltage power cables, the common practice is to perform a dc insulation resistance test, typically at 1000 V dc, conductor to conductor and conductor to ground (conduit).

There are two applications in which shields are common on low-voltage cables. The first is multiconductor control cables, which may have a shield for each pair of wires and an overall cable shield. The second is multiconductor power cables in which there is an overall shield. These shielded power cables are typically used with motors being fed by adjustable speed drives (ASDs) or similar application. In these two cases, the shield is used to minimize electromagnetic interference (EMI). For the first application, the shield is used to minimize the amount of external EMI gaining access to the control circuits. In the second application, the shield on the power cable helps to minimize the amount of EMI the power cable emits since the ASD can be a source of EMI. The common practice for testing shielded low-voltage cables is to perform a dc insulation resistance test, typically at 1000 V dc, between each conductor and between each conductor and the shield.

Most cables that are rated for use at voltage levels above 600 V are shielded cables. A shielded cable has a conductor in the center, a semiconducting layer over the strands that is surrounded by insulation, a semiconducting layer, and then a metal foil or wire mesh shield that surrounds the whole assembly. Usually another protective layer over the shield makes up the outer jacket of the cable. Prior to the 1960s, most

shielded cables were insulated with oil-impregnated paper. Extruded insulations consisting primarily of plastic or rubber compounds were introduced in the 1950s and became widely used beginning in the 1960s.

For many years, dc hi-pot testing was the traditionally accepted method to judge the serviceability of all types of shielded cables. This method was used for factory acceptance testing, field acceptance testing, and maintenance testing. Generally, if the cable withstood the dc hi-pot test, it was judged to be in good condition and placed (or placed back) into service.

DC hi-pot testing continues to be used for acceptance testing and with newly installed cables and field-aged paper-insulated cables. It is a common practice to hi-pot-test the cables on initial installation in order to verify that the cables were not damaged when they were pulled into place and that all the splices and/or terminations were installed properly. The voltage level selected usually is lower than factory test levels, typically at 80% of the dc equivalent of the factory test level.

Beginning in 1994, research and field data raised serious questions about whether dc hi-pot testing might damage or cause premature failure of extruded cables, especially field-aged cross-linked polyethylene (XLPE) insulated cable. EPRI studies (see EPRI Reports TR-101245 [B13] and EL-6902 [B12]) produced the following conclusions regarding XLPE cable:

- DC hi-pot testing of field-aged cable reduces its life.
- DC hi-pot testing of field-aged cable generally increases water tree growth.
- DC hi-pot testing before energizing new medium-voltage cable does not cause any reduction in cable life.

As noted in IEEE Std 400-2001 [B25]: "Testing of cables that have been service aged in a wet environment (specifically, XLPE) with dc at the currently recommended dc voltage levels may cause the cables to fail after they are returned to service. The failures would not have occurred at that point in time if the cables had remained in service and had not been tested with dc." That standard also indicates other testing has shown that "… even massive insulation defects in extruded dielectric insulation cannot be detected with dc at the recommended voltage levels."

5.2.2.3.1 Deterioration mechanisms

Partial discharge (PD) and water intrusion are the two age-related deterioration mechanisms of primary interest for both laminated [paper-insulated lead-covered (PILC)] and extruded [XLPE and ethylene propylene rubber (EPR)] cable designs. Although the source of PD and the process by which water enters the insulation are different for laminated and extruded cables, these forms of deterioration have become a primary focus for cable manufacturers and owners.

PD can occur primarily in voids in the insulation of cables and cable accessories. Within a PILC cable, voids may result when the insulating oil migrates (e.g., due to elevation differences or cracks in the lead sheath or incorrect assembly of terminations) away from an area within the cable. Voids in extruded cable systems can occur due to extrusion problems, improper handling during installation, or errors in termination assembly.

Water intrusion—whether it travels through a crack in the lead sheath of a PILC cable or permeates through the outer layers of an extruded cable—can result in deterioration. Moisture decreases the dielectric strength of the insulation and provides a path for leakage current or other forms of deterioration within the insulation. However, most cable experts are convinced that wet paper insulation and "water trees" (so named for their characteristic visual pattern) in extruded insulation do not initially produce PD. Boggs et al. [B7] describe how "water trees" convert (probably due to transient overvoltages) to "electrical trees." It is commonly accepted that "electrical trees" do produce PD.

5.2.2.3.2 Field testing methods for shielded power cable

IEEE Std 400-2001 [B25] establishes six categories of field tests for shielded power cable:

a) DC testing
b) Very low frequency testing
c) Oscillating wave testing
d) Power frequency testing
e) PD testing
f) Dissipation factor (DF) testing

5.2.2.3.3 Comparison of test methods

The tests listed in 5.2.2.3.2 fall into two groups: Categories a, b, c, and d are withstand tests, and categories e and f are condition assessment tests.

- Withstand tests involve applying an overvoltage. They are go/no-go tests that provide no trendable data. A key concept of withstand tests is that if the overvoltage does not cause the cable to fail, the insulation condition is then considered adequate. All withstand tests require the cable to be deenergized, disconnected, and tested with a special voltage source.
- Condition assessment tests involve measuring characteristics of the insulation. A key concept of assessment tests is that data obtained from these tests can be trended over time to help determine whether and to what extent the insulation has deteriorated. Although some methods for performing these tests involve applying an overvoltage, the overvoltage is not intended as a withstand test that might cause failure of a weak spot.

5.2.2.3.4 PD tests

There are several methods for detecting and measuring PD. Some methods involve deenergizing, disconnecting, and powering the cable from a special voltage source while other methods allow the cable to remain energized at normal line voltage. Both methods of PD testing will detect and measure PD. Should "electrical trees" exist, it is likely that they will progress to failure quickly. PD testing would be more valuable if performed in conjunction with DF and power factor (PF) testing.

5.2.2.3.5 DF tests

When ac voltage is applied to insulation that is in pristine condition, the cable performs much as a capacitor would: Capacitive (charging) current will flow based primarily on insulation type, the cable length, and insulation geometry. Essentially no resistive current will flow, and a near-zero PF results. PF is the ratio of resistive current to total current. DF is the ratio of resistive current to reactive current. Since this value can also be calculated as the tangent of the angle formed between the vector values of total current and reactive current, DF is also referred to in IEEE Std 400-2001 [B25] as "tan δ." For small values of resistive current, PF and DF are approximately equal. Any form of deterioration that results in an increase of resistive current will cause a corresponding increase in PF and DF. Since moisture in PILC cable decreases insulation resistance and allows resistive leakage current to increase, the result will be an increase in insulation PF and DF. Similarly, the presence of "water trees" in extruded cable will increase resistive leakage current. According to the manufacturers of DF testing equipment, the presence of moisture in PILC cable and "water trees" in extruded cables can be identified with such equipment. All forms of available PF and DF test equipment require the cable to be deenergized, disconnected, and tested with a special voltage source.

The reader should be aware that some cable manufacturers are recommending that dc overpotential testing not be performed on their cables due to the phenomenon known as *treeing*. Analysis of cable failures over the years has indicated that dc testing on solid dielectric insulation (as used in XLPE cables) causes the appearance of treeing and subsequent insulation failure. It is recommended that, before conducting any dc overpotential test on cable, the manufacturers be contacted for guidance concerning their specific products.

5.2.3 Power frequency ac tests

The most common ac insulation test is ac overpotential testing at 50/60 Hz. The capacitance of the insulation is a large factor in ac testing. With dc insulation testing, the capacitance of the insulation charges up over time, and the residual leakage current is an indication of the resistance of the insulation. This phenomenon is not true of ac insulation testing. Since the voltage is changing at 50/60 Hz, the leakage current may be predominantly the capacitive charging current of the insulation under test. For this reason, ac overpotential testing is usually a pass/fail type of test in which “passing” means that if no evidence of distress or insulation failure is observed by the end of the total time of voltage application (usually for 1 min) during the ac overpotential test, the test specimen is considered to have passed the test.

IEEE Std C37.20.1-2002 [B17] specifies the value of ac test voltage for 600 V class equipment as 2200 V ac. It also states that, when testing in the field after the equipment has been installed, the maximum value is 75% of the test value or 1650 V ac.

Typically, switchgear, panel boards, and bus ducts are tested using ac voltage. As discussed in 5.2.2, the rise time of the ac hi-pot test significantly stresses the insulation and air gaps more than dc and thus provides a better test on switchgear and panel board insulation.

As a word of caution, the test instrument used to provide the overpotential has a volt-ampere rating and will shut off to protect itself from overload. When performing an ac overpotential test, an adequate test instrument is needed. A commercially available ac hi-pot test set capable of putting out 50 kV at 50 mA will be adequate to test most medium-voltage circuit breakers and switchgear, but it will not be capable of testing even a short run of 480 V bus duct.

The ac overpotential test set must have the capability of continuously providing the required charging and leakage current at the test potential. Because of the high capacitance of large motors and transformers, an ac overpotential test may not be the best test to perform. In 5.2.4, insulation PF testing will be discussed, which can be a more valuable test.

5.2.4 Insulation PF/DF testing

Insulation PF/DF testing is another special type of ac insulation testing. When performing insulation PF/DF testing, the phase relationship between the applied test voltage and the resulting leakage current is determined. Since the leakage current is essentially in phase with the applied voltage, it constitutes a component commonly referred to as the *dielectric watts-loss*. As explained earlier, insulation systems can be considered as capacitors, with the charging current leading the leakage current associated with dielectric watts-loss by 90°. The vector addition of the leakage current and the charging current will equal the total current, which will be at an angle largely determined by the amount of leakage current through the insulation. By measuring the cosine of the angle between the leakage current and the total current, the percent PF can be determined.

This test uses a special test set that supplies voltage and current at 50/60 Hz (see Figure 5). The volt-amperes and watts are measured with the test set, and the PF is determined.

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Figure 5—Insulation PF testing

The primary use of insulation PF testing has been on medium- and high-voltage transformers, circuit breakers, and bushings, particularly when they are oil-filled. Because of the high dielectric strength of oil, a dc insulation resistance test may not detect a problem unless the equipment is about to fail. PF/DF testing provides a means to evaluate the condition of the whole or parts of the insulation system and to track the deterioration of the insulating system as it ages. Many firms have contributed test data on transformers, bushings, and circuit breakers for several decades; thus historic trends have been created on many of the common makes of equipment. PF/DF testing supplies additional data for evaluating a piece of equipment that has been in service and for which no prior test data exist. This test is an extremely useful tool to help predict equipment failure so that the equipment can be scheduled for replacement prior to failure. Utilities across the United States have been performing PF/DF testing of their large transformers and circuit breakers for many years and trending the information to help determine replacement or major repair needs.

5.3 Protective device testing

Any piece of equipment whose primary function is to detect an electrical abnormality or failure, such as an overload or fault, and to automatically initiate the removal of the problem is generally referred to as a *protective device*. A fuse, for example, senses excessive current flow and opens to interrupt the flow of current. Some relays would be classified as "protective" while other relays would be classified as "control" or "alarm," depending on what action the relay initiates. A relay would be considered a protective relay if it trips open a circuit breaker, switch, or motor contactor when it detects an electrical fault. A relay that operates an indicating light or an annunciator, on the other hand, would not normally be considered a protective relay, but would be considered an alarm relay.

The most common types of protective devices are protective relays, fuses, and circuit breakers with integral trip units. Fuses and most low-voltage circuit breakers are self-contained, where the sensing and operating devices are all in a common housing. Medium- and high-voltage circuit breakers, motor starters, and spring-loaded switches usually have separate protective devices, such as protective relays, that work together as a system to perform the overall protective function. Typically, PTs and/or CTs provide voltage and/or current to the protective relay. The relay provides an output contact to operate a circuit breaker, motor starter, or spring-loaded switch when a predetermined level of voltage, current, power, frequency, etc., is reached.

Several issues should be considered when testing any molded-case, insulated-case, and low-voltage power circuit breaker as well as testing any protective relay. It is advisable to follow the manufacturer's instructions, if available. In the absence of the manufacturer's instructions, NEMA AB 4 [B43], IEEE Std 1458 [B36], NFPA 70B-2006 [B45], or ANSI/NETA MTS-2007 [B3] should be consulted. Regardless of the instructions used, the manufacturer's time-current curves should be used so that the device will operate as intended and designed. Validating with the curves is vital to the protective device coordination study (see 5.3.1) as well as the arc-flash hazard analysis (see 4.1). These devices should operate as designed, published, and adjusted or set in order to have an electrical power system that is reliable and maximizes safety.

5.3.1 Protective relays

Protective relaying is a broad subject. Only an overview can be given here.

There are three major objectives in protective relaying. First, a protective relay serves to provide rapid clearing time of electrical faults to minimize incident energy values to reduce arc-flash hazard exposure to personnel. Second, a protective relay serves to protect equipment (i.e., locate and isolate overloads, short circuits, undervoltages, and other types of electrical problems quickly in order to minimize damage). Third, the protective device that is closest to the problem should operate first to clear the problem, and no other device should operate unless the closest one fails. This concept, known as *selective tripping* or *selectivity*, maintains service to as much of the electrical system as possible by isolating only the problem area. In order to achieve these objectives, each relay must function as it was designed, and the relays must function in conjunction with the other protective devices in the system. Having all the protective devices function as one overall protective system is called *protective device coordination*.

Each protective device has specific parameters within which it has been designed to operate. Just as a single element fuse has a value of current above which it opens, it takes a specific amount of time for a given current to melt the link away and open the fuse. Manufacturers of fuses publish time-current curves that show how long it takes a fuse to operate for varying current values. Generally, the higher the current is, the shorter the clearing time will be.

This same inverse current-versus-time concept is used for overcurrent relays and for low-voltage circuit breakers. Relays and low-voltage circuit breakers (with internal trip units) have a range of "pickup" operating current that causes them to operate. In many cases, this value of current is adjustable. By properly

selecting the type, characteristic, and/or setting of fuses, relays, or circuit breakers, the system can be coordinated so that the device that is closest to the problem opens before any device upstream of it does. It is necessary to select compatible time-current characteristics of the devices for the entire system in addition to selecting the proper settings for the devices.

Prior to performing protective relay testing, a coordination study should be completed to determine the proper settings to which the relays should be calibrated. This study is usually done by the design engineer when the system is first installed. If there have been revisions or additions to the system, a new study may be necessary.

Once the coordination study has been completed, the relays need to be calibrated to the proper settings, and input/output logic needs to be properly programmed and validated. Special test sets, available for this purpose, inject currents and voltages, as necessary, and time the various operations and logic sequencing of the relays. This type of testing is usually performed by a technician who specializes in this area. Depending upon the relay to be calibrated, quite complex relay test equipment may be required, and in-depth training in protective relaying may be needed to properly commission and test the relay.

It is important to realize that testing the protective relay is only one part of the protective device coordination. The PTs and/or CTs plus the wiring to the circuit breaker are all necessary for the protective relay to function properly. These items can be verified by functional testing. For electromechanical relays, such as an overcurrent relay, the disc is moved until the contact closes and the circuit breaker trips. (Most circuit breakers have a “test position” to perform this test where the controls are connected but the main power connections are open between the circuit breaker and the medium-voltage bus.) The voltage and current signals can be verified with the circuit breaker in operation using a voltmeter, ammeter, and, if needed, a phase angle meter. On the electronic relays, there is often a “meters” mode in which the relay will display the values it is receiving for voltage and current directly. When available, the meters mode should be used to verify not only that the PTs and CTs are connected properly, but also that the PT and CT ratios are set correctly in the electronic relay.

5.3.2 Low-voltage circuit breakers

Low-voltage circuit breakers come in the following three major types:

a) Low-voltage power (air-frame) circuit breakers

b) Molded-case circuit breakers (MCCBs)

c) Insulated-case circuit breakers (ICCBs)

Low-voltage power circuit breakers start with a frame size of 600 A and go up to 5000 A. The sensing unit that operates the breaker on a short circuit or overload may be either an oil-dash pot with springs and copper coils (for older breakers), CTs, and an electronic trip unit or some other current detection and tripping system, such as an external protective relay. With an electronic trip unit, the number of possible settings and trip functions has made it easier to coordinate circuit breakers with other protective devices.

MCCBs and ICCBs are similar in mechanical construction and insulation. The circuit breakers’ contacts and operating mechanisms are totally enclosed in a molded plastic housing. Both are normally tested and rated in accordance with UL 489 [B51]. The difference between the two is a MCCB has a single-step stored energy mechanism while the ICCB has a two-step stored energy mechanism. For both, the current-carrying parts, mechanisms, and trip devices are completely contained within a molded case of insulating material.

— The cover and base of smaller MCCBs are designed so that the MCCBs cannot be opened for maintenance. The main contacts of MCCBs cannot be removed; however, some MCCBs are available with field-installable accessories. MCCBs are available in stationary or plug-in construction with circuit breaker enclosures that can be flush or surface mounted. They are

available in a large number of continuous-current and interrupting ratings. The smaller continuous-current ratings are equipped with thermal-magnetic or magnetic-only trip units. A thermal-magnetic trip unit is made up of two pieces: a thermal unit to sense overload that uses two dissimilar metals and a magnetic unit to trip on short circuit. Larger sizes of MCCB are available with thermal-magnetic or electronic (static) trip devices.

— The case of the ICCB is designed so that it can be opened for inspection of contacts and arc chutes and for limited maintenance. Most manufacturers offer designs that permit replacement of accessories, and some designs permit replacement of the main contacts. ICCBs are available in both stationary and draw-out construction. They are generally characterized by a two-step stored energy mechanism, larger frame sizes, and higher short-time withstand ratings than MCCBs. Electronic trip units are standard.

The most thorough test for all three types of circuit breakers is by primary injection testing. A special test set that puts out high (fault-level) current at a low voltage (typically 6 V ac to 20 V ac) is used to functionally test the circuit breaker. These test sets have built-in timing functions; therefore, the breaker can be tested at various currents in order to verify that it operates within the published time-current specifications that are provided by the manufacturer and that it is calibrated to perform in accordance with the arc-flash and coordination study.

For circuit breakers that have electronic trip units, it is often possible to do secondary injection testing. This test is usually done with a special test set that is designed for the trip unit. It injects low-level test currents into the trip unit, directly testing the trip unit, its trip output, and the trip coil. For many styles of electronic trip units, it does not test the trip unit's power supply, interconnecting wiring, or CTs. For this reason, primary injection testing is the preferred method of maintenance testing, as it tests the entire circuit breaker overcurrent protective system (e.g., CTs, wiring, shunt trip device) in a manner that is similar to how the breaker would operate during a fault condition.

In addition to testing the tripping characteristics of the circuit breaker by injecting fault current, it is also normal practice to test the insulation resistance (usually at 1000 V dc) and the resistance of the current-carrying components. Such testing is often referred to as a *contact resistance test* or a *microhmmeter test*. Often the primary source of problems with low- and medium-voltage circuit breakers is the contact pivot point. The pivot is lubricated from the factory. However, after being in service, the lubricant dries out over time, and the pivot area wears rapidly. The contact resistance can be measured directly with a digital low-resistance ohmmeter (usually in microhms) or indirectly by performing a millivolt drop test. A millivolt drop test is performed by using a primary injection test set to inject rated continuous current through the breaker while measuring the millivolt drop across the breaker's contacts. It is a comparative test between each phase of the breaker in which the millivolt reading typically should not differ by more than 50% between phases.

Power circuit breakers have mechanical adjustments and inspections that should also be periodically checked. The manufacturer's instructions list the adjustments for each model.

5.3.3 Instrument transformers

There are two common designations of instrument transformers: current transformers (CTs) and voltage transformers (VTs) or, as the latter are more commonly known, potential transformers (PTs). The function of an instrument transformer is to reduce the level of voltage or current so that the protective relay or metering does not have to be rated for full line voltage or current.

The insulation resistance, turns ratio, and polarity may be tested in both CTs and PTs. Insulation resistance testing is discussed in 5.2.2. The turns ratio is a factor of the number of turns of wire in the primary winding to the number of turns of wire in the secondary winding. The polarity is determined by which direction the wire was wound around the iron core. This direction determines the relationship between the primary winding terminal (H1) and the secondary winding terminal (X1) so that X1 is positive with respect

to X2 at the same time that H1 is positive with respect to H2. The correctness of polarity is important to the correct operation of many relays and metering instruments.

Two additional tests are often performed on CTs: “burden” and “saturation” tests. The burden on a CT is the amount of impedance connected to the secondary winding as a load, usually in the form of protective relays or metering. The burden test consists of injecting a known current level (usually 1 A ac to 5 A ac) into the load (usually from the shorting terminal block of the CT circuit) and measuring the voltage at the point of injection. The impedance (or burden) of the circuit is the ratio of the voltage measured to the current injected.

A saturation test is performed to find out the voltage at which the iron in the CT saturates. A known voltage source is connected to the secondary of the transformer and is raised in steps, while the current value is recorded at each step. When saturation is reached, the given voltage changes cause much larger changes in current.

The saturation test is used in conjunction with the burden test to make sure that the CT is capable of operating the load (usually protective relays) to which it may be subjected. If the burden on the CT is too high, it may go into saturation and be unable to maintain its proper ratio. When this situation happens, protective relays may trip too slowly or not at all due to an insufficient level of current from the CT secondary.

The level of testing needed for PTs and CTs depends to a large extent on the application. The voltage and current ratio is important for all applications. The polarity is important for all directional relays and most relays that are receiving both voltage and current signals. The saturation tests are important if there are many devices, particularly if they are electromechanical relays, in series. Polarity and saturation tests are usually performed only as a maintenance test when the tests were not performed during acceptance testing. The ratio tests and insulation tests are commonly done if maintenance is performed on the PTs and/or CTs.

5.4 Analytical tests

Analytical tests address specific aspects of a piece of equipment or system under test. The tests are usually more specialized to the equipment under evaluation and may utilize test equipment that is designed for that specific test.

5.4.1 Winding resistance

Winding and contact resistance tests are similar in that both are looking for a very low ohmic value since they are measuring the resistance of a component that is supposed to conduct electricity. A Kelvin bridge has long been a standard method of measuring low values of resistance and is still in use today. Digital meters are available that are capable of measuring very low values (milliohms or microhms) of resistance. The typical digital low-resistance ohmmeter uses four terminals (to eliminate lead resistance) in which a direct current is injected into the conductor to be measured and the voltage drop across the conductor is measured.

Microhmmeters can be used to measure the resistance of bus joints and cable joints as well as the closed contacts of a circuit breaker or motor starter as discussed in 5.3.2.

Winding resistance differs from contact resistance in that the inductance of large windings can interfere with the operation of the test set. Certain test sets available commercially are designed specifically for large transformer and motor windings, cases for which a standard low-resistance ohmmeter is not adequate. Specific-purpose transformer ohmmeters also have safety advantages over traditional bridges in that they will automatically discharge any inductive voltage buildup that may occur in the winding during the test.

When the windings are discharged, the test set provides an indication that it is safe to remove the test leads, and this feature reduces the likelihood that an arc or shock will occur.

5.4.2 Transformer turns ratio (TTR) testing

The voltage across the primary of a transformer is directly proportional to the voltage across the secondary, which is a ratio of primary winding turns to secondary winding turns.

In order to verify that the transformer was wound properly when it was new and to help locate subsequent turn-to-turn faults in a service-aged winding, it is common practice to perform a TTR test. One method is to energize the primary winding with a known voltage (that is less than or equal to the winding's rating) and measure the voltage on the secondary winding. However, since source test voltages can fluctuate, it is often more accurate (and safer) to use a test set designed for TTR testing that creates the test voltage internally and thus gives a direct readout of the ratio measured. A properly administered TTR test will also indicate whether winding polarity is correct.

5.4.3 Motor surge comparison testing

Motor surge comparison testing finds weak insulation between winding turns by utilizing a high-voltage pulse. Two identical high-voltage pulses are introduced into two windings of a motor. The propagation of the pulse through one winding is compared to the propagation of the identical pulse through the winding next to it. An oscilloscope (usually built into the surge tester) is used to look at the traces and to compare them. The patterns should be identical (or nearly so) and can appear as one trace (two superimposed traces) if both windings are acceptable. A turn-to-turn failure (or a failure to ground) is indicated by two distinctly different traces on the oscilloscope.

Motor surge comparison testing has been used by electric motor repair facilities for many years. Now portable models are available for field testing (see Figure 6). Motor surge comparison testing has proven to be a valuable tool in detecting the early stages of a turn-to-turn winding failure.

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Figure 6—Motor surge comparison testing

5.4.4 Time-travel analysis

Time-travel analysis is primarily performed on medium- and high-voltage circuit breakers. The test consists of plotting the voltage that is applied to the trip coil (or close coil for closing tests) and the movement of the breaker mechanism versus time with a high-speed recorder such as a light beam oscillograph. The two most common values recorded are “velocity” and “displacement,” which are the speed of contact movement and the distance the contacts move. In addition, by analyzing the plot during closing, the opening and close-trip-close operations contact sequence (to see whether the contacts are closing simultaneously), and excessive contact, bounce can be determined.

5.4.5 Infrared (thermographic) scanning

Infrared, or thermographic, scanning is a method that locates high-resistance connections (“hot spots”) by using a camera that turns infrared radiation into a visible image (see Figure 7). This test is performed while the equipment to be scanned is in service and carrying normal load current, and this scheduling is a significant advantage as it does not interrupt normal production. Extreme caution should be exercised due to the exposure to energized conductors and circuit parts. The operator should follow electrical safety-related work practices and utilize the guidance of NFPA 70E-2009 [B46].

The most common use of infrared scanning is to locate loose or corroded connections in switchboards, panel boards, bus ways, motor starters, and other electrical connections. It is also useful to investigate nonelectrical heat sources, such as motor bearings that are overheating, and to verify proper radiator and pump operation in liquid-filled transformers. It is a comparative type of test in which the person who performs the scan is looking for an area that appears hotter than a similar area, such as a lug connection on phase “A” as it compares to similar connections on phases “B” and “C.” (See Figure 7.) The person should be aware of how unbalanced loading, windage, emissivity, reflection, etc., may affect the appearance of heating and thereby give an indication similar to looseness.

One limitation of infrared scanning is that the equipment has to be carrying enough load for the hot spots to be visible. At lower loads, not enough heat may be generated to locate a problem, even when the connections may be significantly loose.

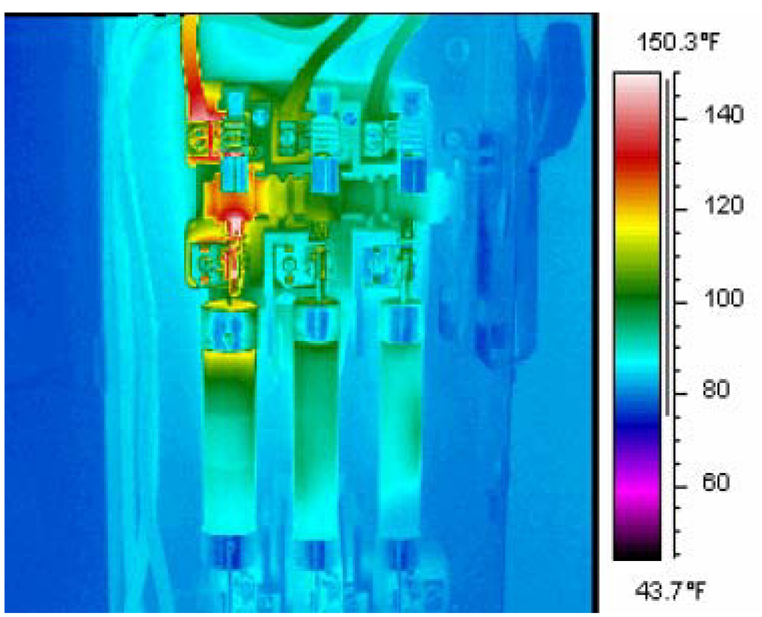

Figure 7—Thermal image of a fused disconnect

5.4.6 Oil testing

Many medium- and high-voltage transformers and circuit breakers utilize different types of oils for insulation and cooling. Analysis of the oil has proven to be a dependable method of locating existing or potential problems with transformers. One of the most obvious problems to significantly reduce the insulation value of the oil is contamination, such as moisture or, for circuit breakers and load tap-changers, carbon. Oil can be tested on site by measuring the voltage at which dielectric breakdown occurs with a specific test set that is designed for this purpose.

Oil samples may be sent to a testing laboratory for a series of quality tests. Measurement of the acidity provides an indication of how much oxidation or contamination the oil has experienced. Interfacial tension, the force that is required to rupture the surface tension at an oil-water interface, is also an indication of possible oxidation or contamination.

One of the most successful tests in determining whether a transformer winding has experienced hot spots, corona discharge, or arcing is the dissolved gas-in-oil analysis test. An oil sample is removed from the unit with a special cylinder that is air tight, and the gases that are dissolved in the oil are analyzed by a gas chromatograph. By determining the type and amount of gas that has been dissolved in the oil, analysis can be made about the internal integrity of the transformer winding and internal structure.

This technology is also applied to load tap changers as well as oil circuit breakers. By analyzing the types of gasses that appear in the oil and their ratios, problems may be predicted and corrected before they cause a failure. The criteria for these devices are different from those for transformers, but the basic methodology and theory are the same.

5.5 Grounding tests

Grounding is a broad subject that has an entire standard dedicated to it: IEEE Std 142-2007.

Ground testing is also covered in detail by standards, including IEEE Std 81-1983 [B23] and IEEE Std 81.2-1991 [B24]. An overview of the testing procedures given in IEEE Std 81-1983 is given in 5.5.1 through 5.5.3.

5.5.1 Grounding electrode test

The 2008 Edition of NFPA 70, National Electrical Code® (NEC®) [B44], uses the term *grounding electrode* for the electrical connection to earth. The test utilized to determine the resistance between a grounding electrode and the earth is called a *fall-of-potential test* or *three terminal test*. It is performed by connecting a test set that provides a known current between the grounding electrode to be tested (C1) and an auxiliary electrode driven in the ground (C2) for the purpose of testing. The voltage is then measured between the electrode under test and another auxiliary electrode. This voltage-sensing, auxiliary electrode is driven into the ground between the other two in a sampling of places. The resistance that is obtained from these measurements should have a flattening of the curve when plotted versus the distance between the test rod and the current rod. The resistance to earth is determined by dividing the voltage by the current. Modern earth resistance testers provide resistance readouts directly with no calculation needed.

5.5.2 Two-point resistance tests

Two-point resistance tests are used to measure the resistance of the equipment grounding conductor and its bonding of the electrical equipment. This type of test is similar to the low-resistance measurements that are taken for contact resistance tests, and the same test equipment can be used. The purpose of this test is to measure the resistance of a test specimen to a known reference point.

5.5.3 Soil resistivity test

Soil resistivity is a measure of resistance per unit length of a uniform cross section of earth, usually expressed in ohm-centimeters. It is performed with a four terminal test set that uses four equally-spaced electrodes driven into the ground. The current flows between the outside two, and the voltage is measured between the inside two. The earth resistivity is equal to the reading of the test set, times 2Π, times the distance between two stakes (in centimeters).

The reader is cautioned that soil and rock are often layered with strata of different resistivity. Probe spacing is representative of the depth of measurement. A geophysicist, with knowledge of local geological formations, is best suited to interpret results from the Wenner test on anything but an isomorphic (single layer) soil structure.

Soil resistivity is an early engineering activity required to design underground ground grids for substations and large electrical equipment prior to civil development. It also is just a snapshot in time and varies considerably with moisture content. This test is typically done only for new construction, not as a maintenance test.

5.6 Functional testing

Functional testing consists of simulating various normal and abnormal conditions and monitoring the system performance for proper operation. This test can be as simple as opening and closing a circuit breaker electrically or as complex as performing transient stability tests on an emergency generator. Functional testing is slightly different when done from a maintenance viewpoint as compared to acceptance testing.

If proper acceptance testing is performed on the initial startup of the system, installation problems such as the miswiring of alarm or control circuits should be found and easily corrected.

The problems a maintenance engineer may encounter usually pertain to deteriorated equipment, adjustment problems, modified designs, and system expansions that have been added since the initial installation. The protective devices should be operated to verify that they function properly. This recommendation is particularly true for protective relays since the relay is only one part of the protective system. Where emergency generators and/or transfer switches are part of the electrical distribution system, there is no better functional test of the entire system than tripping the normal source circuit breaker and observing the system for proper operation.

If the electrical distribution system was not acceptance tested when initially installed, much more extensive functional testing should be performed during initial maintenance periods. Common problems that are frequently encountered include neutral conductors that are grounded downstream of the main bonding jumper (on low-voltage ground-fault systems), improper CT polarity, problems in the control and alarm circuits, and wiring errors between switchboard sections where wiring was revised or completed in the field.

5.7 Testing procedures and specifications

There are many sources of information on testing and maintenance of electrical equipment. The magnitude alone can be a formidable barrier to establishing an effective maintenance program because of the time needed to sort through all the applicable references and apply the material to a specific set of circumstances. To assist the reader in quickly grasping particular needs, an overview of the most applicable references is provided in 5.7.1 through 5.7.3, along with a bibliography in Annex A.

Testing procedures should also include safety-related job planning. Many of the tests described in these subclauses utilize high voltages, which have a chance of injuring the worker doing the test. Bystanders who come into the area without realizing the hazard can also be injured. Testing procedures should require the following at a minimum:

a) Training on the hazards of the test
b) Barricades around the testing area
c) Warning signs around the testing area
d) List of lockouts so that no backfeed is created

5.7.1 Sources of electrical equipment testing and maintenance information

In addition to each manufacturer's instructions, the following is an alphabetical listing of the groups or organizations that provide procedures and specifications for electrical testing and maintenance:

a) American National Standards Institute (ANSI)
b) American Society for Testing and Materials (ASTM)
c) Association of Edison Illuminating Companies (AEIC)
d) Institute of Electrical and Electronics Engineers (IEEE)
e) Insulated Cable Engineers Association (ICEA)
f) InterNational Electrical Testing Association (NETA)
g) Association of Electrical and Medical Imaging Equipment
h) National Electrical Manufacturers Association (NEMA)
i) National Fire Protection Association (NFPA)
j) Occupational Safety and Health Administration (OSHA)

5.7.2 NFPA 70B-2006 [B45]

The development of NFPA 70B began in 1968 when the NFPA Board of Directors established a committee "to develop suitable texts relating to preventive maintenance of electrical systems and equipment used in industrial-type applications with the view of reducing loss of life and property. The purpose is to correlate generally applicable procedures for preventive maintenance that have broad application to the more common classes of industrial electric systems and equipment without duplicating or superseding instructions that manufacturers normally provide."

The document provides reasoning for performing preventive maintenance, economic justification discussions, and detailed procedures for maintenance activities. Maintenance procedures are given for typical items of electrical equipment.

NFPA 70B-2006 offers the core of an excellent EPM program by providing much information for direct use by facility engineers and maintenance personnel. With the addition of specific instructions from the manufacturers' literature, most electrical equipment maintenance needs are covered.

5.7.3 ANSI/NETA MTS-2007 [B3]

The specifications in ANSI/NETA MTS-2007 cover the suggested field tests and inspections that assess the suitability for continued service and reliability of electrical power distribution equipment and systems.

The purpose of these specifications is to verify that tested electrical equipment and systems are operational and within the tolerances of applicable standards and manufacturers and that the equipment and systems are suitable for continued service.

The subjective assessment required by this NETA maintenance standard is unique compared to other ANSI standards in that it deals with the evaluation of service-aged equipment. While technicians performing tests and inspections on new equipment deal with finite test values, technicians working with service-aged equipment should form recommendations based on judgment.

Technicians performing these electrical tests and inspections should be trained and experienced concerning the apparatus and systems being evaluated. These individuals should be capable of conducting the tests in a manner that minimizes safety risks and with complete knowledge of the hazards involved. They should be able to evaluate the test data and make a judgment on the continued serviceability or nonserviceability of the specific equipment, based on the recommendations of the standards and manufacturers.

Test technicians should have knowledge of and experience with the specific device under test. Additional personnel qualifications are as follows:

a) Testing organizations: Owners utilizing testing companies are encouraged to require that each on-site crew leader hold a certification in electrical testing from a recognized standard, such as ANSI/NETA ETT-2000 [B2].
b) Manufacturers' service personnel: Field service personnel of the manufacturer of the equipment being evaluated should be certified by the manufacturer to perform these electrical tests and inspections. The manufacturer should provide sufficient documentation to satisfy the owner that its service personnel are trained and qualified to perform these electrical tests and inspections.
c) In-house testing personnel: Owners having in-house testing personnel should utilize an independent, outside certification organization or have a system of qualification that provides an equivalent level of assurance that their personnel are qualified to perform electrical testing. Owners are encouraged to utilize a recognized standard such as ANSI/NETA ETT-2000 [B2] to determine that their electrical testing personnel possess the training, experience, and proof (examination) requirements now being promulgated by various governmental agencies.

6. Maintenance of standby power equipment

6.1 General description of preventive maintenance practices

Preventive maintenance for electrical equipment consists of planned inspections, testing, cleaning, drying, monitoring, adjusting, corrective modification, and minor repair in order to maintain equipment in optimum operating condition and maximum reliability. In addition to routine preventive maintenance, it is important to maintain written records that document maintenance performance and test measurements. Also, drawings, such as connection wiring diagrams, one-line diagrams, and block diagrams, are necessary for maintenance work.

6.1.1 Precautionary measures

Vital precautionary measures that should be considered a part of preventive maintenance are as follows:

— It should be made certain that the installation and ventilation of the emergency or standby power systems will not be adversely affected by unauthorized storage or accumulations of dirt.
— Regular test responsibilities should be placed on trained and qualified personnel, and tests should be scheduled frequently to verify reliable operation.

— Gasoline and, to a lesser extent, diesel fuels deteriorate when stored for extended periods of time. Inhibitors can be used to reduce the rate of deterioration, but it is sound practice to operate a system utilizing these fuels so that total operating time will result in a complete fuel change cycle. The period of time between complete fuel change should be determined for the specific fuel being stored.
— In case of life-limited components, a sufficient quantity of spares should be maintained, and they should be replaced according to the manufacturers' directions.

Use manufacturers' recommended procedure frequencies to establish a preventative maintenance program and then adjust the frequencies from experience.

6.1.2 Personnel requirements

Personnel who maintain standby or emergency power systems should be required to have specific training and qualifications, as well as certain tools, manuals, and access to equipment, so that preventive maintenance can be carried out effectively.

A list of these personnel requirements are as follows:

— An understanding of the manufacturer's test procedures and frequency
— Special training at the manufacturer's location for equipment start and routine maintenance
— A complete set of specialized and normal tools for required maintenance procedures on site

For the following list, the manufacturer typically can assist in developing this tool set:

— A complete set of shop manuals and list of required spare parts (with location notes)
— A manual of test procedures with step-by-step details
— Physical access to system equipment to perform tests within required frequencies
— Management and/or supervisory support to perform the tests within required frequencies

6.1.3 How to use Clause 6

Many different types of emergency and standby power systems are on the market today. This clause presents a consolidation of general preventive maintenance recommendations that are organized into subclauses (6.2 through 6.7) according to system components. These general recommendations can then be applied to emergency and standby power systems that are formed from the various components.

6.2 Internal combustion engines

6.2.1 General

Internal combustion engines that are commonly available include those that use natural and bottled gas, gasoline, and diesel fuel. Since there are more similarities than differences in their maintenance requirements, these engines are grouped together.

Long life and high reliability are characteristics to be expected from these types of prime movers, but only if properly maintained. EPM programs will greatly contribute to the service life and reliability.

In establishing an EPM program for these engines, the best starting point is the manufacturer's service manual. This document will provide a guide for specific points to be checked and for frequency of inspection. These reference points can then be modified to fit particular installation and operating conditions.

6.2.2 Operating factors affecting maintenance

More than any other factor, lubrication determines an engine's useful life. Various parts of the engine may require different lubricants and different frequencies of lubricant application. It is important to follow the manufacturer's recommendations regarding type and frequency of lubrication.

Because dirt and corrosion are major causes of equipment failure, no engine should be considered properly maintained if it is not cleaned. Dirt increases the difficulty of inspecting engine parts and interferes with heat conduction. Before performing any inspection on service, carefully clean all fittings, caps, fillers, level plugs, and their adjacent surfaces to prevent contamination of lubricants and coolants. Keep all dirt, dust, water, and sediment out of the fuel to prevent engine damage and clogging of fuel filters and injectors. In addition, bacteria in the presence of water can form sludge over an extended period of time, which will exacerbate the clogging of fuel filters and injectors. Frequently draining any water from the bottom of the fuel tank is the best method to prevent sludge. Visual and laboratory tests of a fuel sample are also of great value.

6.3 Gas turbine

6.3.1 General

The combustion gas turbine, as with any rotating power equipment, requires a program of scheduled inspection and maintenance to achieve optimum availability and reliability. The combustion gas turbine is a complete, self-contained prime mover. This combustion process requires operation at high temperatures. When inspection marking on stainless steel parts is necessary, a grease pencil should be used. Graphite particles from lead pencils will carburize stainless steel at the high temperature of gas turbine operation.

Starting reliability is of prime concern since a delay in starting often means the original need for the unit has passed.

6.3.2 Operating factors affecting maintenance

The factors having the greatest influence on scheduling of preventive maintenance are type of fuel, starting frequency, environment, and reliability required.

a) *Fuel.* The effect of the type of fuel on parts is associated with the radiant energy in the combustion process and the ability to atomize the fuel. Natural gas, which does not require atomization, has the lowest level of radiant energy and will produce the longest life; and the crude oils and residual oils, with higher radiant energy and more difficult atomization, will provide shorter life of parts.

   Contaminants in the fuel will also affect the maintenance interval. In liquid fuels, dirt results in accelerated wear of pumps, metering elements, and fuel nozzles. Contamination in gas fuel systems can erode or corrode control valves and fuel nozzles. Filters should be inspected and replaced to prevent carrying contaminants through the fuel system. Clean fuels will result in reduced maintenance and extended lives of parts.

b) *Starting frequency.* Each stop and start subjects a gas turbine to thermal cycling. This thermal cycling will cause a shortened parts life. Applications requiring frequent starts and stops dictate a shorter maintenance interval.

c) *Environment.* The condition of inlet air to a combustion gas turbine can have a significant effect on maintenance. Abrasives in the inlet air, such as ash particles, require that careful attention be paid to inlet filtering to minimize the effect of the abrasives. In the case of corrosive atmosphere, careful attention should be paid to inlet air arrangement and the application of correct materials and protective coatings.

d) *Reliability required.* The degree of reliability required will affect the scheduling of maintenance. The higher the reliability desired, the more frequent the maintenance required.

6.4 Generators

6.4.1 General

The generator requires consideration for ambient temperature control since the unit is in a deenergized state most of the time. Also, a program of scheduled inspections and maintenance is required to achieve optimum availability and reliability.

6.4.2 Operating factors affecting maintenance

Keeping equipment clean is of primary importance in generator preventive maintenance. Dust, oil, moisture, or other substances should not be allowed to accumulate on the equipment. Ventilation ducts should be kept clean to allow maximum cooling air in the generator. The importance of keeping windings clean cannot be overemphasized; dust, dirt, and other foreign matter can restrict heat dissipation and deteriorate winding insulation. A layer of dust as thin as 0.76 mm (30 mil) can raise the operating temperature of generator windings l0 °C.

The best method for cleaning a generator of loose and dry particles is to use a vacuum cleaner with proper fittings. Blowing with 210 kPa (30 lbf/in^2) compressed air can also be employed, but this method has a tendency to redeposit the particles. Wiping with a soft, clean rag has the disadvantage of not being able to remove dust from grooves and inaccessible places. Buildup of grease and oil can be removed by conservative use of nonflammable solvents. Megohmmeter readings should be taken before and after cleaning and drying. If the insulation resistance is too low, dry out the machine with heat for several days. If low insulation resistance persists, there should be further analysis of contributing factors to the low insulation resistance values.

Regularly scheduled inspections should include checking for tightness; checking all wires for chafed, brittle, or otherwise damaged insulation; and checking bearings, brushes, and commutator for proper operating condition. Inspect for leakage of bearing grease inside the generator housing. If moisture has accumulated in the generator, the unit should be dried, and strip heaters or other methods should be utilized to prevent the condition from recurring. To dry the unit, external heat should be applied to reduce the moisture content. Internal heat may then be applied by introducing a low-voltage current through the windings. The winding temperature should be monitored to prevent insulation damage during the drying operation.

Brushes and connecting shunts should be inspected for wear and deterioration. Remove the brushes one at a time and check for length. Be sure the brushes move freely in their holders. Brush holders should be checked for proper tension. Most brushes will operate satisfactorily with 17 kPa to 21 kPa (2.5 lbf/in^2 to 3.0 lbf/in^2) of brush cross section, but the manufacturer's recommendation should be checked. Replace or repair brush holders that cannot provide adequate tension. Brushes should be replaced when worn to the

point that tension cannot be adjusted properly, usually a brush length of about 1.27 cm (1/2 in). In most cases, replace complete sets rather than single brushes. Be sure the shunt leads are properly connected.

After placing new brushes in their holders, carefully fit the contact surface of the brushes to the commutator by using first #1, then #00, abrasive paper (garnet paper is recommended). Cut the abrasive paper into strips slightly wider than one brush. Insert the strip under the brush with the smooth side toward the commutator. Draw the strip in the direction of rotation only until approximately 90% contact has been made with the arc of the commutator. After the brushes have been seated, clean the carbon dust from the commutator and brush assemblies.

Examine brushes for sparking under load. Commutator brushes may have slight sparking; slip ring brushes should have none at all. Examine brushes for chattering or for frayed shunts or chips indicative of chattering. If correction of the spring tension does not alleviate the chattering, consult an expert for advice on brush grades, brush current density, brush pressure, etc.

Commutators should be smooth and have a light- to medium-brown color. A rough or blackened generator commutator may be lightly polished with a commutator dressing stone fitted to the curvature of the commutator, but the underlying cause should be determined. If not available, use #00 abrasive paper with a block of wood shaped to fit the curvature of the commutator. Do not use emery cloth.

All brushes should be lifted and the generator should be driven while slowly moving the polishing block back and forth. The mica insulation between commutator bars should be undercut 0.16 cm to 0.08 cm (1/16 in to 1/32 in). As the commutator wears down, the mica will cause ridges resulting in bouncing of the brushes. If this condition exists, the mica should be undercut, and the commutator resurfaced by a qualified service facility. Do not use lubricants of any kind on the commutator.

Generator bearings should be subjected to careful inspection at regularly scheduled intervals. The frequency of inspection, including addition or changing of oil or grease, is best determined by a study of the particular operating conditions. Sealed bearings require no maintenance and should be replaced when worn or loose. When the generator is running, listen for or record noise, and feel the bearing housing for vibration or excessive heat. Use vibration analyzing equipment to obtain the vibration signature on antifriction bearings.

The failure of an insulation system is a common cause of problems in electrical equipment. Insulation is subject to many conditions that can cause failure, such as mechanical damage, vibration, excessive heat or cold, dirt, oil, corrosive vapors, and moisture from either processes or just humid weather. To aid in detecting any of these damaging effects, an insulation resistance test is used to determine insulation quality. The test is simple, convenient, and nondestructive. A carefully controlled hi-pot test may be performed at less frequent intervals.

The location of the engine-generator set for an emergency or a standby power system is an important aspect of maintenance. If the set is located indoors, provisions should be made to ensure there is space for repair and maintenance procedures to be accomplished. If the set is located outdoors, dusty and corrosive environments should be avoided, and engines should be equipped with an oil heater and engine-coolant heater. With proper preventive maintenance, a generator will provide reliable and lengthy service.

6.5 Uninterruptible power supply (UPS) systems

6.5.1 General

UPS systems are installed because the load requires an uninterruptible source of power or a power source of specific quality. Therefore, additional precautions should be taken when isolating a UPS for maintenance. Be familiar with the critical loads supplied by the UPS, and notify the appropriate personnel when the UPS should be removed from service for maintenance.

When a shutdown of the system is required for maintenance, the UPS system should be placed in the bypass mode, or for redundant systems, the load should be transferred to the redundant units. The UPS system to be maintained should be completely isolated from input and output power, including batteries. Many UPS systems have unique isolating procedures to prevent an outage to a critical load. These procedures should be followed. An additional safety precaution is required to verify that stored energy capacitors are discharged.

6.6 Stationary batteries

6.6.1 General

The primary objective of any battery maintenance program is to enable the battery installation to meet the emergency requirements of the system to which it is connected over its design life. Secondary objectives are to achieve optimum life of the battery and to determine when the battery requires replacement. To be effective, the maintenance should be both regular and consistent. In addition, since much of the analysis of the data relies upon comparison to previous data (i.e., trend analysis), the data should be corrected to standard references. For example, within the United States, the reference values are voltage and capacity at 25 °C and electrolyte full charge specific gravity at 25 °C and at a specific level reference (e.g., the high-level line or the midpoint between the high- and low-level lines).

Maintenance of a battery usually begins at the time of installation. However, if the battery will be in storage longer than the battery manufacturer recommends, maintenance should begin while the battery is in storage. IEEE Std 450-2002 [B30] describes the data to be taken during installation as well as maintenance to be performed during storage, if required, for vented lead-acid batteries. IEEE Std 1188 [B35] provides the same information for valve-regulated lead-acid (VRLA) batteries. IEEE Std 1106-1995 [B33] provides the same information for nickel-cadmium batteries.

Since much of the maintenance performed on a battery is done with the battery in service, the work methods used should follow the protective procedures outlined in the appropriate reference. In addition, these methods should preclude circuit interruption or arcing in the vicinity of the battery. One of the reasons for this concern is that hydrogen is liberated from all vented-cell types of batteries while they are on float or equalize charge or when they are nearing completion of a recharge. VRLA cells will also liberate hydrogen when their vents open. Therefore, adequate ventilation by natural or mechanical means must be available to minimize hydrogen accumulation. Additionally, the battery area should be mandated as a “no smoking” area.

6.7 Automatic transfer switches

Automatic transfer switches require maintenance, as do most components of electrical installations. The automatic transfer switch is usually applied where two sources of power are made available for maintaining power to a critical load. The necessity of providing safe maintenance and repair of an automatic transfer switch requires shutdown of both power sources or installation of a bypass switch. The bypass switch is used to isolate the automatic transfer switch while maintaining power to the critical load. For periodic maintenance inspections where deenergization is impractical, a two-way bypass isolation switch combined with an automatic transfer switch as part of a UPS system can be provided. This type of switch allows for periodic testing and maintenance.

Annex A

(informative)

Bibliography

Additional information may be found in the following sources:

[B1] ANSI/NETA ATS-2009, Acceptance Testing Specifications for Electrical Power Distribution Equipment and Systems.[8]

[B2] ANSI/NETA ETT-2000, Standard for Certification of Electrical Testing Personnel.

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